Urban Landscape Management Practices as Tools for Stormwater Mitigation by Trees and Soils

David K. Mitchell

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
In
Forest Resources and Environmental Conservation

Susan D. Day
Brian D. Strahm
Theresa M. Thompson

August 6, 2014
Blacksburg, Virginia

Keywords: mulch, urban soil, stormwater management, green infrastructure,
urban trees, runoff, urban forest

Urban Landscape Management Practices as Tools for Stormwater Mitigation by Trees and Soils

David K. Mitchell

ABSTRACT

As urban land expands across the globe and impervious surfaces continue to be used for constructing urban infrastructure, stormwater treatment costs and environmental damage from untreated stormwater will rise. Well designed urban landscapes can employ trees and soils to reduce stormwater runoff flowing to streams and treatment facilities. Typical urban soil, however, is compacted and restricts tree growth via high soil strength and inadequate gas exchange. A site preparation method that deeply incorporates compost and includes trees for long term carbon input and pore development was evaluated in the urban setting of Arlington, Virginia. Three species were used in that study of 25 streetside plantings. The site preparation affected soil at 15-30 cm by lowering soil bulk density by 13.3%, and increasing macro-aggregate-associated carbon by 151% compared to control plots, and resulted in 77% greater tree growth during the first year after transplant. In a second experiment, rainfall simulations were used to evaluate common landscape mulch materials for their ability to prevent compaction from traffic as well their affect on surface runoff before and after traffic. When plots were subjected to heavy rainfall, (>97 mm/h) mulches were found to reduce sediment loss 82% and 73% before and after traffic, respectively. Runoff rates from wood chips were only 0.19 ml/s faster after traffic while rates from bare soil and marble gravel with geotextile increased 2.28 and 2.56 ml/s, respectively. Management of soils, trees and landscapes for stormwater benefit could reduce cost of wastewater treatment for municipalities and can prevent environmental degradation.

Acknowledgments

This research was installed in cooperation with Virginia Tech, Arlington County Parks and Recreation and the Arlington County Division of Transportation. Funding for this work was provided in part by the Virginia Agricultural Experiment Station and the Program McIntire Stennis of the National Institute of Food and Agriculture, U.S. Department of Agriculture. The project was also funded in part by the Tree Research and Education Endowment Fund and the Institute for Critical Technology and Applied Science at Virginia Tech.

John James, John Peterson, Velva Groover, Jordan Endahl, Daniel Debruler, Stuart Hupp, Sarah Gugercin and Trevor Carr were all quite helpful with study installation and data collection. My advisor Susan Day has been very helpful with guiding this research from planning to analysis, as well as setting up the project with the folks in Arlington. Christine Simpson and Vincent Verweij were instrumental in the installation of the experiment in Arlington. I would also like to thank my wife Rachel for her constant love and support.

Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

Urban areas are expanding worldwide, especially as developing nations become more industrialized. The expansion of urban lands requires conversion of rural landscapes to developed ones, which creates environmental problems by changing local hydrology. Urban lands can be characterized by a high density of human structures such as buildings, roads, parking lots and sidewalks, which are typically designed to shed precipitation into engineered drainage structures. 'Impervious cover' and 'impervious surface' are terms that encompass built structures that have very low initial abstraction, i.e., runoff occurs shortly after rain begins, and thus contribute to the altered hydrologic characteristics of urban areas compared to the pre-development conditions. This increased impervious surface results in urban streams swelling quickly during rain events and then retreating quickly once precipitation stops, as well as reduced stream flow between rain events. Impervious cover also warms runoff, which can degrade habitat of cold-water fish and influence erosion. As impervious cover within a watershed increases, flooding occurs from smaller rain events. With more frequent floods, the rate of channel erosion increases which can undermine bridges, expose pipelines and lead to sediment problems downstream.

During urban development, vegetation is removed and soils are compacted and covered by impervious materials. The few soils that are not covered after development are usually quite compact, become saturated quickly and do not drain well. Thus, in addition to there being more impervious surface, the amount of precipitation stored in the remaining soil and vegetation decreases, and runoff increases. Although there is considerable interest in parcel-level stormwater management approaches in urban areas (e.g., low impact development, bioswales), little attention has been directed to attenuating stormwater through improving the quality and functionality of landscape trees and soils on a wider scale in urban land.

Urban soil needs to support both buildings and green infrastructure (e.g., plant and soil systems that provide various services to urbanites), but these goals require different physical characteristics: plants need low density soil with fluctuating water and air content, while buildings and roads need the stability of compacted soil. Balancing these two disparate requirements has proven difficult. Soil compaction is frequently encountered in urban areas due to traffic and construction activities directly on or adjacent to urban soils. Because compacted soils cannot accept large volumes of water before becoming saturated, saturation excess occurs rapidly and higher runoff volumes are produced from smaller rain events on urban soils compared to natural, agricultural or forest soils; in effect, compacted urban soil can act like impervious cover. Soil compaction also limits gas exchange and water movement in the soil matrix, restricting root gas exchange and making plant growth challenging. Restoring low bulk density to disturbed soil is difficult; preventing soil compaction is easier, though not always possible.

If urban soils can be protected and enhanced to improve stormwater capture, environmental and financial benefits may result. For example, increasing the role of infiltration in the urban water balance may improve base flows to local streams. Additionally, the streams may be cooler due to the presence of trees shading impervious surface and reducing input of runoff from hot surfaces in the summer, thereby improving fish habitat. In cities with combined sewers, managing stormwater via trees and soils may also result in economic benefits to localities by reducing stormwater volumes flowing to wastewater treatment facilities, directly lowering treatment costs. To realize these economic and environmental benefits, soils in urban areas need to have water infiltration and storage functions restored in a cost effective way. Once restored, the soils need to be protected from further degradation from urban activities such as foot traffic that are known to compact soil. When soils function well, trees are able to grow larger and provide more ecosystem services including stormwater mitigation. Protecting functioning soil from damage is necessary to sustain tree health for the long term, as well as to preserve the soil's ability to provide stormwater and carbon storage services.

This research addresses the potential of urban trees and soils to attenuate stormwater on a wider scale than is typically seen with low impact development, using both soil rehabilitation and compaction prevention to improve soil functionality and enhance landscape trees. The first study examines the ability of different landscape mulch materials to prevent soil compaction and preserve the ability of the soil to slow and store precipitation after simulated foot traffic. The use of mulches for preventing erosion, intercepting precipitation and slowing runoff is also examined. The second study examines the potential of a soil rehabilitation technique called "soil profile rebuilding" that uses deeply incorporated organic amendment and trees for stormwater mitigation as well as decreasing soil density, increasing carbon storage and encouraging tree root growth. The focus of this work is on increasing the ecosystem services that can be provided by urban trees and soils, particularly in the category of stormwater management. The development of stormwater BMPs has partially decentralized stormwater management—toward centralized management at the parcel level instead of the city or district level. If all urban land could function at a higher level of ecosystem service provision, stormwater management could become dispersed to utilize every tree and non-impervious surface in a city more effectively, possibly lowering maintenance requirements of hyper-functioning stormwater BMPs, and increasing associated ecosystem services such as air pollution mitigation and psychological well-being as well.

Chapter 2: Literature Review

The urban landscape

Global urban populations are expanding

The proportion of the human population residing in urban areas is increasing globally. Urban dwellers currently make up over 80% of the total population in North America, and over 70% in Latin America and Europe. Urban populations are predicted to increase in all regions of the world (United Nations, 2012). Concomitantly, urban land area is expected to triple during the period of 2000-2030, an increase of 1.2 million km^2 (Seto et al., 2012). Urban areas can be defined on the basis of increased density of people and their structures relative to adjacent areas (e.g., Adams and Lindsey, 2012), or on a basis of energy consumption and waste production relative to area (e.g., Rees, 1997). Because of the limited land area inherent in these definitions, urban areas rely on engineered infrastructure to mediate problems associated with urbanization. Trees can help alleviate some pressures on the infrastructure (i.e. interception, funneling and storage of precipitation (Johnson and Lehmann, 2006)) as well as mitigate some other undesirable side effects of built structures (i.e. the urban heat island (Akbari et al., 1997)). In the future, costs associated with engineered infrastructure could be reduced by planning for trees and green spaces to carry some of the stormwater management load, while also improving the quality of life for urban inhabitants through providing many ecosystem services (Zhang et al., 2012).

Urbanization creates environmental problems locally and downstream

Urban landscapes are dominated by impervious surfaces such as parking lots, roofs, and roadways. For example, in Beijing, green spaces of all types only account for 3.7% of the total area of the city (Zhang et al., 2012). The higher percentage of impervious surface in urban lands relative to rural areas drastically changes the local hydrologic cycle (as reviewed in Shuster et al., 2005) with decreased base flows (Klein, 1979) but also higher peak flows and increased total runoff at the expense of soil water storage (Booth, 1991) and increased flood frequency (Moscrip and Montgomery, 1997), as well as degraded water quality (Klein, 1979) (quantity issues reviewed in Arnold Jr. and Gibbons, 1996; and quality issues reviewed in Makepeace et al., 1995). The effect of impervious area is so pronounced, that it has been suggested as an environmental indicator for natural resource protection in urban planning (Arnold Jr. and Gibbons, 1996). More recently, effective impervious area, which discounts runoff from impervious surface that drains to pervious areas, has been suggested as a better metric for predicting impact of development (Guo, 2008). In addition to pavement and buildings, compacted soils have also been included in definitions of impervious surface (Arnold Jr. and Gibbons, 1996; Gregory et al., 2006), and compacted soils adjacent to impervious surfaces may act as extensions of the impervious surface (Shuster et al., 2005), due to low infiltration rates (Pitt et al., 2008).

The increase in urbanization has led to urban stormwater runoff becoming a significant contributor to impairment of waterways in the US (USEPA, 2004). The interconnection of impervious surfaces via pipes, gutters and constructed waterways leads to decreased infiltration of precipitation, caused by the disconnection of precipitation and soil. The resulting stream response to impervious surfaces is increased peak flow volume, reduced time to peak flows and reduced base flows (Endreny, 2005), although leaking water infrastructure and over irrigation of landscapes can increase base flows in arid urban catchments (Garcia-Fresca and Sharp Jr, 2005; Lerner, 2002; Townsend-Small et al., 2013). Increased overall flow volume and decreased minimum size of runoff-producing events in urban catchments increases the rate of erosion in urban streams relative to rural streams (Neller, 1988). Higher peak flows have the potential to overwhelm stormwater drainage systems and flooding can result. Less infiltration, shorter times to peak flows and higher total runoff volume create a need for large stormwater detention facilities (Shuster et al., 2005).

In addition to the issue of increased water volume, urban runoff can have higher temperature and carry contaminants as well. Pollutants accumulated on impervious surfaces are washed into streams, often remaining suspended, and severely degrading the quality of receiving water bodies (Arnold Jr. and Gibbons, 1996; Makepeace et al., 1995). Suspended solids in streams alter receiving water bodies ecologically by increasing nutrient delivery, especially phosphorous (Heathwaite et al., 2005), as well as other contaminants (Bilotta and Brazier, 2008). Heat from urban impervious surfaces is also transferred to stormwater runoff which increases stream temperature and degrades fish habitat (Herb et al., 2008; LeBlanc et al., 1997; Van Buren et al., 2000). Increased stream temperature can also lead to more sediment loss from erosion (Parks, 2012)

Low impact development (LID) strategies which utilize functions of vegetation in the landscape can help manage the quantity and quality of stormwater runoff, although issues with tradeoffs between phosphorous and nitrate-N removal still exist (Dietz, 2007; Dietz and Clausen, 2006; Zhang et al., 2011; Zinger et al., 2013). Urban forests also aid in stormwater management as trees overhanging impervious surfaces intercept precipitation that would otherwise run off of impervious surfaces and into waterways (Wang et al., 2008). The magnitude of the effect of urban forests and their associated soils in stormwater mitigation is considerable. It has been estimated that the urban forest in New York City provides over 35 million dollars in yearly benefits per year from stormwater mitigation (Pepper et al., 2007).

Benefits of urban trees and soils

Trees in urban areas provide a variety of ecosystem services that can mitigate negative aspects of urban land use (as reviewed in Escobedo et al., 2011; and Roy et al., 2012). Many of these services are essential to human life; although they are not typically marketable, they have tremendous value (Costanza et al., 1997). However, many changes in the soil environment associated with urban development such as compaction (Alberty et al., 1984; Day and Bassuk, 1994; Randrup and Dralle, 1997) and elevated pH (Ware, 1990) make growing healthy trees difficult in many urban areas (Patterson, 1977). Trees are relevant to problems associated with water and hydrology, as their presence in the landscape has an effect on runoff amounts (Sahin and Hall, 1996) as well as runoff pathways (Wang et al., 2008).

Trees and soil together are able to attenuate urban stormwater by intercepting and funneling rainwater into the soil (Johnson and Lehmann, 2006), rainwater caught by trees in urban areas would often fall on impervious surfaces if urban trees were not present. Rainfall is also intercepted by tree canopies and subsequently lost to evaporation. Although there is considerable variation among species and storm size, annual rates of rain interception can be more than 30% in an evergreen forest (Rutter et al., 1972). Rain interception may be as high as 79.5% of a 20 mm storm for large open grown trees in full leaf condition (Xiao and McPherson, 2002). Interception prevents some water from reaching soil under trees, and along with stemflow alters the evenness of rain inputs under tree canopies (Jackson and Wallace, 1999).

Roots affect the movement of water into the soil. Tree roots have the ability to transfer water from soil with high water potential (e.g., ponding near the surface) to low water potential (e.g., drier deep layers) via sap flow in living tissue (Burgess et al., 2001). Mitchell et al. (1995) found that live alfalfa roots create macropores that remain stable under the pressures of swelling smectite clay. Dead roots of woody plants also increase the downward flow of water into soils (Devitt and Smith, 2002). Decomposing tree roots can increase hydraulic conductivity and air-filled porosity by over 20% compared to soil without tree roots (Yunusa et al., 2002). Bramley et al. (2003) saw flooded basins with trees drain 2-17 times faster than flooded basins without trees, and tracer dye tests indicated that a large portion of the water drained along root channels.

The service of capturing precipitation and directing a large portion to evaporation (Rutter et al., 1972; Xiao and McPherson, 2002) and soil (Jackson et al., 2000) can effectively reduce stormwater runoff in urban areas, especially from smaller storm events. Bottomland tree species can grow roots into compacted soil when it is very wet, due to its reduced strength (Day et al., 2000), potentially increasing drainage through such soils (Bartens et al., 2008). Utilizing the ecosystem services provided by trees and soils for stormwater management can have large economic benefits for local governments when compared to engineered (grey) infrastructure solutions (McPherson et al., 2011; Zhang et al., 2012). Tree roots and canopies have an effect on stormwater pathways in the urban environment, and have the ability to slow down and reduce urban stormwater quantity. Because trees route precipitation into the soil, avoiding paved surfaces, they can be used with soils as a tool for stormwater mitigation.

Urban soils can absorb precipitation or produce runoff

The small amount of open soil (soil that is not paved or covered by buildings) in urban areas is often of poor quality and very compacted, reducing water infiltration (Stephens et al., 2012). Even sandy soils can effectively act as impervious surfaces when sufficiently compacted (Gregory et al., 2006). Open soil areas in cities are generally intended to support green space (e.g., street medians, parks, building landscapes, etc.) and could be used as tools for stormwater management while simultaneously providing the intended green space if the soil can be maintained with high permeability (as discussed in Zhang et al., 2012). Whether runoff is generated from urban soils depends on the size and intensity of the rain event, and the water storage capacity of the soil, as well as the initial water status before the rain event (Berthier et al., 2004). Surface crusts that develop on bare soil decrease infiltration rates (Morin and Benyamini, 1977), thus a lack of vegetation may also contribute to increased runoff. Open soils near impervious surfaces such as roadways are often less permeable and more compact than they were before the road was built, due to disturbance and compaction during construction (Craul and Klein, 1980; Lichter and Lindsey, 1994). Because the increased runoff from adding impervious surface over sandy soil is greater than the increase from development on clayey soils, it has been suggested that areas with sandy native soils should be used for green spaces, while areas with more clayey native soil should be used for development (Sjöman and Gill, 2013). The ability of soil to attenuate stormwater can be improved via increasing drainage and lowering bulk density to allow for more water storage, tree roots can improve infiltration (Bramley et al., 2003) and organic matter additions can decrease bulk density (Rivenshield and Bassuk, 2007). In addition, tree roots have the ability to improve soil structure over time, enhancing hydrologic properties and maintaining soil health. This suggests that soil restoration methods using trees and organic amendments to improve surface infiltration and soil permeability could be developed and used in urban settings to improve water quality in local streams.

Trees shade impervious surface, mitigating the heat island and lowering runoff temperature

Stormwater quantity is not the only problem caused by increases in impervious surface, runoff quality is also degraded. One result is thermal pollution of stormwater which can degrade cold-water fish habitat in local streams. This problem may be mitigated with increases in urban tree canopy (Jones et al., 2012). Urban trees provide shade that can mitigate heating of adjacent surfaces (USEPA). For example, roof and wall surface temperatures can be reduced by as much as 25°C due to shade from trees in late summer in Sacramento, CA (Akbari et al., 1997). Surface temperatures of asphalt pavements can approach 60°C during the middle of a summer day in suburban Tokyo (Asaeda et al., 1996). Such heat stored in pavement contributes to increased runoff temperature (Jones et al., 2012), and is a main driver of the urban heat island effect and a contributor to smog formation, which can also be mitigated by urban trees (Akbari et al., 2001). A study by Solecki et al. (2005) concluded that increasing urban trees would be a cost effective method of mitigating the urban heat island effect in New Jersey. More directly, shade provided by urban tree canopy could reduce runoff temperature since increased solar radiation on paved surfaces prior to a rainfall event results in increased temperature of the runoff from those surfaces in Minnesota (Herb et al., 2008). Trees reduce the amount of heat in surfaces that could be transferred to stormwater (Jones et al., 2012) and inclusion of trees in biofiltration systems may help reduce runoff temperature. Traditional stormwater detention BMPs such as wet ponds and constructed wetlands contribute to thermal pollution of streams during summer months due to un-shaded standing water being heated by the sun. Additionally, outlets for these ponds are often located near the normal water surface, allowing the warmer surface water to be released first (Jones and Hunt, 2010). Infiltration based stormwater control measures have been shown to decrease temperature of stormwater between inlet and outlet points (Jones and Hunt, 2009; Winston et al., 2011). If soils can be managed to be quite permeable, resist compaction and facilitate growth of large trees, more stormwater could be attenuated through the soil instead of flowing quickly to urban streams, fewer pollutants (including heat) would be transferred to streams, and loads on engineered stormwater infrastructure would be reduced, lowering costs to municipalities.

Soil Characteristics important for tree growth and stormwater infiltration

Trees depend on good quality (Jim, 1998) and large quantities (Day and Amateis, 2011) of soil to grow to their potential and maintain long-term health. Urban soil compaction has been recognized as an inhibiting factor to growth of urban trees for at least three decades (e.g. Jim, 1993; Zisa et al., 1980). At a finer scale than compaction, soil physical characteristics such as density, structure and organic matter content are important for soil permeability. The physical characteristics are often also the limiting factor for root growth of urban trees (Day and Amateis, 2011), as high bulk density and soil strength can limit root penetration (Materechera et al., 1991; Pan and Bassuk, 1985) and gas exchange (Stepniewski et al., 1994). In particular, soil structure, "the spatial heterogeneity of the different components or properties of soil" (Dexter, 1988) or the arrangement of the pores and particles in soil, plays a significant role in soil permeability (Abu-Sharar et al., 1987; reviewed in Alaoui et al., 2011) and is closely linked to soil organic carbon (SOC) content, as soil aggregates are held together largely by organic compounds (Oades, 1993). Thus, SOC is essential for building soil structure that favors permeability, and when soils are compacted that structure is often lost.

Soil carbon

In urban areas, however, C cycling, and consequently aggregate formation, is often disrupted. Worldwide, SOC is a large pool for the sequestration of atmospheric carbon with the upper 100cm of soil estimated to hold between 1462 to 1548 Pg of SOC (Batjes, 1996). Organic matter in soils is essential for nutrient cycling, especially in terms of phosphorous availability (Tiessen et al., 1994). Soil organic matter inputs are often interrupted in urban settings as fallen leaf litter is collected and disposed of instead of being allowed to decompose in place (Sloan et al., 2012). Carbon storage in urban soil has been estimated. Total carbon from the surface to

75 cm depth in a 35 year old urban lawn in Liverpool, UK was approximately 5 kg C m^{-2} (Beesley, 2012). Pouyat et al. (2006) evaluated SOC content in six US cities: Atlanta, GA; Baltimore, MD; Boston, MA; Chicago, IL; Oakland, CA; and Syracuse, NY. Soil organic carbon densities for the total area of those cities ranged from 5.49 kg C m^{-2} (Chicago) to 7.83 kg C m^{-2} (Atlanta), but were higher in pervious areas. If such estimates are representative of urban lands, urban soil holds approximately the same amount of C as a typical temperate Alfisol (5.5 kg C m^{-2}; similar to temperate hardwood forest) but less than a typical temperate Mollisol (9.1 kg C m^{-2}; similar to a temperate grassland) (Eswaran et al., 1993). Variations in methods of bulk density determination may result in overestimation of SOC (Throop et al., 2012). Compact soils may also alter plant growth processes in such a way that organic matter additions are reduced (Brevik et al., 2002) although minor compaction may protect existing soil carbon and slow its decomposition (Deurer et al., 2012). Chen et al. (2013) found that common urban land development practices depleted soil carbon, from labile as well as the most stable pools. Total C increases in urban soils with soil age and is higher in soils close to roads (Park et al., 2010). Soil organic carbon also plays a role in the formation and stabilization of aggregates in surface soil layers (Tisdall and Oades, 1982). Thus, methods of land development that include the goal of increasing C stored in soil have potential as a tool to prevent the loss of soil C, as well as preserve soil quality for plant growth and stormwater management as land uses change.

Soil aggregates

Soil aggregates are made up of primary soil particles bound together by organic matter and electrical charges, these secondary particles form the structure of a soil, and allow movement of water into plant roots and deep soil layers. Macropore presence in finer textured soils is influenced by both soil aggregates (Booltink et al., 1993) and by root exploration (Mitchell et al., 1995). Soil macropores play an important role in infiltration of water into the soil (Beven and Germann, 1982). Soil with stable aggregates and high macroporosity (i.e. good structure) is necessary for successful growth of most plants (Tisdall and Oades, 1982) because it allows for water infiltration and gas exchange. Soil structural stability is determined by the stability of the aggregates making up the structure. Aggregate stability is influenced by biological activity, including the production of gluing compounds that bind small aggregates, and the growth and destruction of roots and hyphae that bind larger aggregates (Tisdall and Oades, 1982). Inputs of organic matter into the soil become associated with mineral particles and form soil aggregates, within which the organic matter can be protected from decomposition (Jastrow, 1996). Roots and soil fauna play a large role in development of soil macropores (Oades, 1993). Compost additions to urban soil can serve to inoculate the soil with beneficial microbes and make the soil more habitable for the soil fauna that help in formation of macropores. Compost amendments also provide nutrients and pore spaces for root proliferation. Increased root growth will encourage macroaggregate development through binding of microaggregates with roots and fungal hyphae (Jastrow, 1996). As such, compost amendments are likely to be useful for improving stormwater mitigation potential in urban soils not only by improving the soil itself, but also by improving conditions for tree growth.

Soil compaction

Soils with higher bulk density are generally restrictive to growth of woody plants and other vegetation due to higher strength and decreased pore space (Alberty et al., 1984; Kozlowski, 1999; Pan and Bassuk, 1985; Zisa et al., 1980). In addition to restricting plant growth, soil compaction directly affects soil porosity pore size distribution, resulting in slower infiltration rates (Cole and Fichtler, 1983). Surface crusts are more likely to form in the absence of vegetation, and in urban areas petroleum deposits and decayed organic matter can make the crust hydrophobic. A soil with hydrophobic crust and few large pores will have a low ability to infiltrate water, so precipitation often becomes runoff (Craul, 1994). Tree transpiration is reduced in sections of forest that have been subjected to human foot traffic (Komatsu et al., 2007). It has also been suggested that soil compaction along with other harsh elements of the urban environment, stresses trees and can predispose them to attack from pests (Poland and McCullough, 2006). Jurskis (2005) suggests that poor soil conditions can be the primary factor in a chain of events causing tree decline and death. Dead and unhealthy trees are less valuable than healthy trees in the urban forest, as trees without leaves provide little stormwater attenuation benefit (Xiao and McPherson, 2002), and dead trees may become hazards.

Lower infiltration decreases the amount of water stored in soil, and can lead to surface runoff and erosion reducing water available to trees. Soils that have high bulk density may have strength lowered to levels allowing certain species to grow roots under moist conditions, but soils must be able to become very wet for this to happen (Bartens et al., 2008; Zisa et al., 1980). The lack of aeration caused by compaction can also inhibit the infection of root tissue with mycorrhizal fungi (Entry et al., 1996), a class of symbiotic fungi often essential for plant growth. Mycorrhizae also play a role in soil aggregation and thus maintenance of structure (Tisdall and Oades, 1982). Price et al. (2010) found that lawn and pasture soils in the Blue Ridge of North Carolina had quite similar saturated hydraulic conductivity, bulk density and moisture content, while in forest soils, the saturated hydraulic conductivity was higher by an order of magnitude, the bulk density lower by 0.4 g/cm^3 and the moisture content was 30% higher. Urban soils are often plagued with compaction due to foot and vehicle traffic endemic to urban areas. Compaction can also increase the temperature of soils (Donnelly and Shane, 1986).

Processes during urban development include deliberate compaction, vegetation removal and leveling of the soil surface (Park et al., 2010) to support buildings and roadways. Soil compaction may be caused by vehicle and machinery traffic (Alakukku et al., 2003), pedestrian traffic (Cole and Fichtler, 1983), or intentionally during new construction (Alberty et al., 1984). Soil in urban areas that is not subjected to direct traffic can also become compacted by vibrations from adjacent vehicular traffic or mass transit systems (Craul, 1994). Organic soils suffer a smaller loss of total porosity from compactive force than clay soils, although the loss of macroporosity in organic soils is greater. Organic topsoil (0-0.2 m) recovers from compaction faster than clay topsoil does (Alakukku, 1996).

Compacted soil, while necessary for the support of built structures, has a compounding negative influence on urban stormwater management. Compacted soils both produce runoff faster than soils that drain, and prevent growth and survival of trees that are able to prevent runoff. Organic soil amendments such as compost can help alleviate issues with water infiltration when mixed into compacted soil, and also help to create a habitable environment for tree root growth. De-compaction of soils in areas intended for planting in urban areas is essential for green spaces to have a stormwater management function.

Methods of soil modification to reduce runoff and improve root health

Due to the influences of urban soil compaction and the concomitant loss of soil structure on stormwater runoff, both indirectly through their effect on trees and directly through their effect on infiltration rates, there could be considerable benefit to reducing compaction and increasing permeability of urban soils. Compaction can be addressed through replacement (e.g. Watson et al., 1996; Watson, 2002), prevention (e.g. Lichter and Lindsey, 1994) or rehabilitation (e.g. Chen et al., 2013; Layman et al., 2009). In urban settings where impervious surfaces dominate the landscape and adequate soil resources are in short supply, poor quality or disturbed soils are often replaced prior to tree planting. In cases where there are no existing trees, soils often can be amended to improve their quality. Soil replacement, compaction prevention and soil rehabilitation all have situations in which they are more useful, and financial costs are variable and site specific. The merits of each option are discussed below.

Soil replacement

Replacing soil with manufactured growing substrate requires design on a case-by-case basis as well as transporting large volumes of material (Sloan et al., 2012). Partial soil replacement with compost amended soil around mature trees increases crown growth and root density in treated areas (Watson et al., 1996), but may not increase root development outside the zone of replacement (Watson, 2002). Replacing urban soils with structural soil (engineered mixes that can be compacted to support pavement while still allowing root growth), can allow tree roots to grow under pavement. These mixes use uniformly graded gravel, lava rock or expanded slate to form a skeleton that will support sidewalks or plaza areas (Bartens et al., 2010; Grabosky and Bassuk, 1995; Sloan et al., 2012). Suspended pavement is another method of allowing tree roots to grow below sidewalks (discussed in Bartens et al., 2010; and Smiley et al., 2006). Use of suspended pavement would likely coincide with use of a manufactured or imported soil. Soil on site could be used beneath suspended pavement, if the quality was acceptable (as was done in Smiley et al., 2006). Structural soils may be used for stormwater attenuation (Bartens et al., 2008; Bartens et al., 2009; Xiao and McPherson, 2011), but the potential of suspended pavement designs for stormwater attenuation is unknown. Soils for rain gardens in urban areas may be manufactured in areas where native soil drainage is slow (Davis et al., 2009), on-site soil may be used if permeability is high enough (Dietz and Clausen, 2005). It is logical that high permeability soils might cause plants to become water stressed, while no studies have shown this explicitly, increased growth from inclusion of a saturated zone in biofilters as observed by Zhang et al. (2011) supports this idea. While engineered soil mixes are fitting for many situations, the cost to install such systems suggests that other methods of increasing or maintaining permeability over large areas may be preferable.

Prevention of compaction

High quality urban soils are rare, and often good quality soils are degraded by equipment traffic and construction processes during development (Jim, 1993). Avoiding compaction during construction operations is more efficient than trying to restore low bulk density and high porosity to the soil after damage has occurred (Lichter and Lindsey, 1994). Avoiding, rather than remediating soil compaction is also desirable in agricultural settings (Alakukku et al., 2003). Amending soils after disturbance can be difficult and tends to be more expensive than protecting soil from disturbance. Amelioration of compacted soil when trees are present is likely to damage roots and be harmful to the health of the trees (Jim, 1993). Urban soil tends to improve in quality as time passes since disturbance, with higher soil organic matter, more available P and N, and decreased bulk density in soils on older sites compared to newer soils (Scharenbroch et al., 2005). Hydraulic conductivity (Woltemade, 2010), and SOM, total C and N (Park et al., 2010) increase with time since disturbance in landscapes, but the increase occurs slowly, on the timescale of decades, and tree growth is limited during that time. Thus, preventing soil compaction is more efficient than remediating large areas of disturbed soil.

Gravel and bark mulches were found to prevent compaction on a simulated construction site better than plywood or an unprotected control (Lichter and Lindsey, 1994). Randrup and Dralle (1997) found that involvement of landscape professionals during the construction process, specification quality and whether loosening of soil was specified had no effect on post construction soil compaction levels. Careful planning and enforcement of the construction plan with the intention of preserving soil quality in certain areas on new construction sites as well as in situations such as remodeling or adding to existing residences could reduce unwanted soil compaction. However, little effort is required to damage soils to the point that they produce runoff, and specific procedures to prevent compaction would need to be designed for individual sites, especially considering that construction in urban areas often occurs in tight spaces. Changing the status quo is difficult due to issues with communicating a problem that may not be well understood by those who cause it, as well as increasing expense during planning and execution of construction activities. Because these problems exist, sometimes soil damage in areas intended for landscaping is inevitable and methods for restoring soil function are needed.

Soil rehabilitation

Soil rehabilitation methods often utilize organic amendments. Amendment with organic material immediately decreases bulk density because organic materials have lower particle density than mineral soil. For example, compost incorporated at rates of 50% and 33% by volume resulted in bulk density decreases of 11% and 17% for fine and coarse textured soils respectively (Rivenshield and Bassuk, 2007). A meta analysis of studies that deal with organic materials targeted at the arboriculture industry found that incorporating organic amendments in soil benefits soil physical properties more than surface application of the same material (Scharenbroch, 2009). Bark mulch applied over compost-amended soil was found to increase soil carbon, lower bulk density and increase growth of *Cornus sericea* (Redosier Dogwood) more than either surface applied mulch, or compost amendment alone (Cogger et al., 2008). Amending soil with 3 or 4 inches of yard waste compost tilled in to a depth of 7 inches enhances root growth and plant quality of azaleas after 8 months, irrespective of high or low irrigation levels (Beeson and Keller, 2001). Organic amendments applied via air-tillage methods have been shown to improve soil conditions around established trees (Fite et al., 2011).

Soil profile rebuilding (SPR), the technique evaluated in this study, is intended to improve soil qualities for tree growth and water infiltration in the long term (Day et al., 2012). Initially this is done by a subsoiling procedure that breaks up compacted soils and separates clods with veins of compost down to 60 cm or greater depth. Woody plants are included in the technique for long term carbon additions and soil maintenance. Tree roots are known to aid in soil aggregate formation by releasing root exudates, compounds that cement soil particles as well as provide a carbon source for microbial activity in the vicinity (Day et al., 2010a). In SPR, the veins of compost created by the subsoiling procedure are expected to allow for root penetration through soil that would otherwise have limiting bulk density, strength and pore size. Woody plants are expected to continue to input carbon into the soil at deep horizons via root exudates, fine root turnover and mycorrhizal association. This technique has been shown to increase soil carbon stores at depth (Chen et al., 2013).

Soil Profile Rebuilding is expected to increase carbon stores in soil and permeability for the long term, via carbon additions from woody plant root turnover and associated microbes in the system. Black et al. (1998) found high variability in rates of fine root turnover between species in a study using minirhizotrons. Godbold et al. (2006) found the average lifespan of mycorrhizal hyphae to be about 9 days, in a study of *Populus* species. The same study found that 62% of carbon inputs to soil organic matter came from turnover of mycorrhizal hyphae as opposed to fine root turnover, root exudate and litter inputs. The study also showed that elevated atmospheric CO_2 levels increased fine root turnover, contradicting a study by Matamala et al.

(2003) which investigated *Pinus taeda* and *Liquidambar styraciflua* suggesting that CO_2 response is species dependent. A study by Lukac et al. (2003) also reported increases in fine root turnover under elevated CO_2, which also varied between species. However, a study by Heath et al. (2005) showed that increased temperatures in an elevated CO_2 scenario would increase respiration of soil microbes and decrease overall sequestration of root derived carbon. The elevated CO_2 levels found in cities (George et al., 2007; Idso et al., 1998; Ziska et al., 2004) may increase root turnover similar to what was seen in the studies by Godbold et al. (2006) and Lukac et al. (2003) depending on species. Although the effect of elevated CO_2 on root turnover is under debate, belowground biomass allocation was increased, and root distribution was deeper with *Populus alba* and *Populus nigra* in the elevated CO_2 environment of the Free Air CO_2 Enrichment (FACE) experiments (Lukac et al., 2003) and would likely be increased in urban environments as well. The possibility of more and deeper roots under elevated CO_2 makes Soil Profile Rebuilding even more appealing for use in urban environments. The potential for increased root turnover also furthers the goals of the SPR technique.

Because trees and soils offer ecosystem services of stormwater mitigation and C sequestration, maximizing these benefits at low cost would be economically beneficial for cities, especially as society grows more concerned about C pollution. Using existing soil to grow trees and attenuate stormwater is likely more cost effective than soil replacement, and could be used in combination with methods of compaction prevention to maximize benefits. Soil rehabilitation via SPR is intended to be a long term solution to soil degraded by construction, with roots serving to increase soil permeability and continue to store carbon for many growing seasons. The SPR technique has increased both saturated hydraulic conductivity (Chen et al., 2014) and soil carbon stores (Chen et al., 2013) 5 years after installation in a rural setting, and carbon inputs could increase due to higher CO_2 concentrations in urban environments.

Mulching

Mulching is common practice in landscape beds and around planted urban trees in many parts of the world. Mulches can be defined as any primarily non-living material purposely distributed in thin layers on the soil surface and are typically used around plants, although they are also used around infrastructure (light posts) or on trails. Cover crops could be considered living mulches, but in the context of trees, non-living material is more common as it does not compete with trees for water and nutrients or disturb existing tree roots. Mulches have been widely studied for their aesthetic and durability qualities (Skroch et al., 1992), weed reduction ability (Billeaud and Zajicek, 1989), nutrient and organic matter inputs (Atucha et al., 2011), applicability for erosion control (Buchanan, 2002) and their ability to alter soil moisture regimes (Iles and Dosmann, 1999) (as reviewed in Chalker-Scott, 2007). Mulches also have the ability to reduce compaction, but this has not been studied as extensively as other aspects (e.g. Donnelly and Shane, 1986; Lichter and Lindsey, 1994).

Mulches are consistently specified as a top layer in bioinfiltration systems (Davis et al., 2009) for their ability to pre filter runoff and adsorb oil and grease (Hong et al., 2006), and have been studied for their ability to protect soil from erosion. For example, compost layers 3.75 cm thick were found to reduce solids and nutrient loss under rainfall simulation more than hydroseed treatment and control (Faucette et al., 2005). Raw wood chips as typically produced from arboricultural activities were effective at preventing erosion on 55% slopes when applied covering 80% of the soil area (Buchanan, 2002). Mulches have the ability to intercept irrigation water and prevent it from reaching the soil (Gilman and Grabosky, 2004). Fifteen centimeters of shredded hardwood bark mulch improves bulk density, porosity, infiltration rates and hydraulic conductivity of the underlying soil more than herbicide treatments or turf groundcovers in orchards (Oliveira and Merwin, 2001). Organic mulches (wood chips and shredded bark) can keep soil temperatures lower than mineral mulches, and both types reduce soil temperature compared to no mulch (Iles and Dosmann, 1999). Mulches that have small pore spaces (organics and fine mineral mulch) reduce evaporative water losses from the soil better than mulches with large particles and pores (Iles and Dosmann, 1999). Mineral mulches that conduct heat into the soil may help increase root growth in early spring, increasing canopy production, however carbon and nutrient input benefits of organic mulch may outweigh the temperature benefits in areas with poor soils (Iles and Dosmann, 1999). Soil amended with biosolids has been shown to buffer soil against changes in temperature compared to unamended soil, due to decreased thermal conductivity and higher specific heat, due to increased water content (Gupta et al., 1977). The effect of high root zone temperatures on *Gleditsia triacanthos* and *Acer rubrum* have been studied by Graves (1994). The two species were found to tolerate soil temperatures up to 34°C for *G. triacanthos* and 32°C for cultivars of *A. rubrum* before injury. High root zone temperatures can affect the uptake of iron, and can also cause leaf necrosis (Graves, 1994). Soil temperatures at 15 cm depth under trees planted in parking lots were 3°C hotter than under trees planted in undisturbed soil, and temperature under asphalt was up to 10°C hotter (Halverson and Heisler, 1981). In moist soil, the minimum temperature observed for the growth of roots of *Juglans nigra* was 4°C, and root growth metrics increased with temperature to 21°C, the maximum observed (Kuhns et al., 1985). Maximizing time in which soils are within the window of 4 to 32°C could increase root growth, especially if the soil is more able to buffer against the extremes, though increased buffering capacity against temperature could cause a later start for root growth in the spring.

Mulch material has the ability to protect soil from compaction. Hikers have been shown to have a preference for wood chips as a trail covering (Koenker, 2002). Both hardwood bark mulch and gravel mulch are able to prevent compaction from construction traffic when applied at 30 cm thickness (Lichter and Lindsey, 1994). In urban landscapes, however, mulch is typically applied at a depth of 5-8 cm. Nonetheless, ten centimeters of softwood bark mulch also prevents compaction in a forest setting, but application of mulch after compaction does not decrease soil bulk density within two years after application (Donnelly and Shane, 1986). Because mulches can prevent compaction, and are a preferred surface material for hikers, it follows that vegetation near potential walking paths could benefit from paths being mulched. Bark mulch can be used as an effective filter for pollutants in urban stormwater (Ray et al., 2006). Mulch layers at the surface of biofilters removed most of the total suspended solids in synthetic urban runoff (Hsieh and Davis, 2005). Gravel and straw mulches reduced runoff generation and increased infiltration on a clay soil in Texas (Adams, 1966). Mulches therefore are likely to reduce erosion and runoff from compacted soils, such as those found near sidewalk intersections in urban areas; however, there have been no studies addressing the change in the ability of mulches to reduce runoff after trampling.

Conclusion

Urban environments are growing globally, and their impacts to the adjacent environments must be addressed. Management practices within cities have an effect on the areas outside of the city, particularly in the context of stormwater management. Soils in urban areas are usually quite degraded, as they have been subjected to decades if not centuries of construction projects, day to day traffic, and waste inputs from the daily life of urbanites. The result of long term traffic on soils is low pore space, high strength and limited ability to drain—creating a poor environment for plant growth and water regulation. The impervious surfaces in urban environments further reduce the ability of the land to buffer against high volumes of surface runoff.

Few studies have focused on techniques to restore the hydrologic and biotic functions of natural soil to urban soils, but organic amendments have been a common approach to this goal. Compost as a soil amendment has been studied extensively for its effects on plant growth and health, as well as soil physical and chemical properties. Deep (>20 cm) compost incorporation has been less studied, and effects of such amendments on trees and physical/hydrologic properties of deep soil layers is relatively unstudied. In addition, most studies have taken place in the context of crop production or landscape establishment and studies taking place in urban soils are less common. Dispersed stormwater management via LID practices has become more popular, but such practices still rely on draining parcels to certain defined areas. If large areas of the landscape can be returned to near pre-development conditions, stormwater handling LID and traditional stormwater control measures could be reduced for small to medium rain events.

Tree growth and establishment as affected by compost amendments has had some attention in the literature, but usually in the context of amending tree planting holes. Improvement of larger soil areas is likely to increase the lifespan of trees, as soil outside of planting holes will be of equal quality. Because larger trees provide more ecosystem services than smaller trees, improving soil quality could result in a faster return on investment for municipalities through increased growth and survival of new tree plantings. Such benefits must first be quantified if they are to be realized by society.

Mulches have been studied from many perspectives in the horticultural literature, including durability, aesthetics, weed reduction, moisture retention, heat conduction and nutrient and carbon additions. Studies of the ability of mulch to resist or prevent compaction have been done, but have not addressed compaction and sealing at the mulch-soil interface after traffic, and how this affects runoff production. In particular, studies of common ornamental mulches' ability to prevent compaction and store rainwater to reduce runoff are lacking. Mulching is also practiced for erosion control, although this is usually the only intended function, thus, many popular landscape mulches have not been evaluated. Management practices on open soil in urban areas have the potential to affect water quality in urban streams and groundwater, thus more information is needed about the benefits from potential management strategies like walkway surface coverings.

This research will assess a soil rehabilitation method for urban areas that uses on-site soil, evaluating the effects of the method on soil physical and hydrologic properties, as well as monitoring changes in tree growth in the rehabilitated soil, compared to soil in the same urban area that has not had rehabilitation treatment. The method for rehabilitating soils uses a scooping and dumping action to incorporate compost into deep soil layers, followed by tilling, topsoil addition and installation of woody plants. The research will also assess the value of different mulches for preventing soil degradation and subsequently increased runoff from simulated foot traffic. Open soil in areas subjected to frequent foot traffic becomes compacted and can damage the health of nearby trees, as well as contribute to increased stormwater runoff. These projects will contribute to the knowledge of urban soil management for stormwater mitigation and health of the urban forest. We hope this research will contribute widely applicable, low cost tools for managing urban stormwater.

References

Abu-Sharar, T., Bingham, F., Rhoades, J., 1987. Reduction in hydraulic conductivity in relation to clay dispersion and disaggregation. Soil Science Society of America Journal 51, 342-346.

Adams, C.E., Lindsey, K.J., 2012. Anthropogenic ecosystems: The influence of people on urban wildlife populations, in: Niemalä, J. (Ed.), Urban Ecology: Patterns, Processes, and Applications. Oxford University Press, Oxford, NY, pp. 116-128.

Adams, J.E., 1966. Influence of mulches on runoff, erosion, and soil moisture depletion. Soil Science Society of America Journal 30, 110-114.

Akbari, H., Kurn, D.M., Bretz, S.E., Hanford, J.W., 1997. Peak power and cooling energy savings of shade trees. Energy and Buildings 25, 139-148.

Akbari, H., Pomerantz, M., Taha, H., 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Solar Energy 70, 295-310.

Alakukku, L., 1996. Persistence of soil compaction due to high axle load traffic. I. Short-term effects on the properties of clay and organic soils. Soil and Tillage Research 37, 211-222.

Alakukku, L., Weisskopf, P., Chamen, W.C.T., Tijink, F.G.J., van der Linden, J.P., Pires, S., Sommer, C., Spoor, G., 2003. Prevention strategies for field traffic-induced subsoil compaction: A review: Part 1. Machine/soil interactions. Soil and Tillage Research 73, 145-160.

Alaoui, A., Lipiec, J., Gerke, H.H., 2011. A review of the changes in the soil pore system due to soil deformation: A hydrodynamic perspective. Soil and Tillage Research 115–116, 1-15.

Alberty, C., Pellett, H., Taylor, D., 1984. Characterization of soil compaction at construction sites and woody plant response. Journal of Environmental Horticulture 2, 48-53.

Arnold Jr., C.L., Gibbons, C.J., 1996. Impervious surface coverage: The emergence of a key environmental indicator. Journal of the American Planning Association 62, 243-258.

Asaeda, T., Ca, V.T., Wake, A., 1996. Heat storage of pavement and its effect on the lower atmosphere. Atmospheric Environment 30, 413-427.

Atucha, A., Merwin, I.A., Brown, M.G., 2011. Long-term effects of four groundcover management systems in an apple orchard. HortScience 46, 1176-1183.

Bartens, J., Day, S.D., Harris, J.R., Dove, J.E., Wynn, T.M., 2008. Can urban tree roots improve infiltration through compacted subsoils for stormwater management? Journal of Environmental Quality 37, 2048-2057.

Bartens, J., Day, S.D., Harris, J.R., Wynn, T.M., Dove, J.E., 2009. Transpiration and root development of urban trees in structural soil stormwater reservoirs. Environmental Management 44, 646-657.

Bartens, J., Wiseman, P.E., Smiley, E.T., 2010. Stability of landscape trees in engineered and conventional urban soil mixes. Urban Forestry & Urban Greening 9, 333-338.

Batjes, N.H., 1996. Total carbon and nitrogen in the soils of the world. European Journal of Soil Science 47, 151-163.

Beesley, L., 2012. Carbon storage and fluxes in existing and newly created urban soils. Journal of Environmental Management 104, 158-165.

Beeson, R., Keller, K.G., 2001. Yard waste compost as a landscape soil amendment for azaleas. Journal of Environmental Horticulture 19, 222-225.

Berthier, E., Andrieu, H., Creutin, J., 2004. The role of soil in the generation of urban runoff: development and evaluation of a 2D model. Journal of Hydrology 299, 252-266.

Beven, K., Germann, P., 1982. Macropores and water flow in soils. Water Resources Research 18, 1311-1325.

Billeaud, L.A., Zajicek, J.M., 1989. Influence of mulches on weed control, soil pH, soil nitrogen content, and growth of *Ligustrum japonicum*. Journal of Environmental Horticulture 7, 155-157.

Bilotta, G.S., Brazier, R.E., 2008. Understanding the influence of suspended solids on water quality and aquatic biota. Water Research 42, 2849-2861.

Black, K.E., Harbron, C.G., Franklin, M., Atkinson, D., Hooker, J.E., 1998. Differences in root longevity of some tree species. Tree Physiology 18, 259-264.

Booltink, H.W.G., Hatano, R., Bouma, J., 1993. Measurement and simulation of bypass flow in a structured clay soil: a physico-morphological approach. Journal of Hydrology 148, 149-168.

Booth, D.B., 1991. Urbanization and the natural drainage system--impacts, solutions, and prognoses. The Northwest Environmental Journal 7, 93-118.

Bramley, H., Hutson, J., Tyerman, S.D., 2003. Floodwater infiltration through root channels on a sodic clay floodplain and the influence on a local tree species Eucalyptus largiflorens. Plant and Soil 253, 275-286.

Brevik, E., Fenton, T., Moran, L., 2002. Effect of soil compaction on organic carbon amounts and distribution, South-Central Iowa. Environmental Pollution 116, S137-S141.

Buchanan, J., 2002. Wood chips as a soil cover for construction sites with steep slopes. Applied Engineering in Agriculture 18, 679-684.

Burgess, S.S., Adams, M.A., Turner, N.C., White, D.A., Ong, C.K., 2001. Tree roots: Conduits for deep recharge of soil water. Oecologia 126, 158-165.

Chalker-Scott, L., 2007. Impact of mulches on landscape plants and the environment-a review. Journal of Environmental Horticulture 25, 239.

Chen, Y., Day, S.D., Wick, A.F., McGuire, K.J., 2014. Influence of urban land development and subsequent soil rehabilitation on soil aggregates, carbon, and hydraulic conductivity. Science of The Total Environment.

Chen, Y., Day, S.D., Wick, A.F., Strahm, B.D., Wiseman, P.E., Daniels, W.L., 2013. Changes in soil carbon pools and microbial biomass from urban land development and subsequent post-development soil rehabilitation. Soil Biology and Biochemistry 66, 38-44.

Cogger, C., Hummel, R., Hart, J., Bary, A., 2008. Soil and Redosier Dogwood response to incorporated and surface-applied compost. HortScience 43, 2143-2150.

Cole, D.N., Fichtler, R.K., 1983. Campsite impact on three western wilderness areas. Environmental Management 7, 275-288.

Costanza, R., d'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'neill, R.V., Paruelo, J., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253-260.

Craul, P.J., 1994. Soil compaction on heavily used sites. Journal of Arboriculture 20, 69-69.

Craul, P.J., Klein, C.J., 1980. Characterization of streetside soils of Syracuse, New York, Metropolitan Tree Improvement Alliance (METRIA) Proceedings, pp. 88-101.

Davis, A.P., Hunt, W.F., Traver, R.G., Clar, M., 2009. Bioretention technology: Overview of current practice and future needs. Journal of Environmental Engineering 135, 109-117.

Day, S., Seiler, J., Persaud, N., 2000. A comparison of root growth dynamics of silver maple and flowering dogwood in compacted soil at differing soil water contents. Tree Physiology 20, 257-263.

Day, S.D., Amateis, R.L., 2011. Predicting canopy and trunk cross-sectional area of silver linden (*Tilia tomentosa*) in confined planting cutouts. Urban Forestry & Urban Greening 10, 317-322.

Day, S.D., Bassuk, N.L., 1994. Effects of soil compaction and amelioration treatments on landscape trees. Journal of Arboriculture 20, 9-9.

Day, S.D., Eric Wiseman, P., Dickinson, S.B., Roger Harris, J., 2010. Tree root ecology in the urban environment and implications for a sustainable rhizosphere. Journal of Arboriculture 36, 193.

Day, S.D., Layman, R.M., Chen, Y., Rolf, K., Daniels, W.L., Gugercin, S., Harris, J.R., Wiseman, P.E., McGuire, K.J., Strahm, B., Wick, A.F., Mauzy, B., 2012. Soil profile rebuilding, specification for restoration of graded and compacted soils that will be vegetated, p. 5.

Deurer, M., Mueller, K., Kim, I., Huh, K., Young, I., Jun, G., Clothier, B., 2012. Can minor compaction increase soil carbon sequestration? A case study in a soil under a wheel-track in an orchard. Geoderma 183, 74-79.

Devitt, D.A., Smith, S.D., 2002. Root channel macropores enhance downward movement of water in a Mojave Desert ecosystem. Journal of Arid Environments 50, 99-108.

Dexter, A., 1988. Advances in characterization of soil structure. Soil and Tillage Research 11, 199-238.

Dietz, M., 2007. Low impact development practices: A review of current research and recommendations for future directions. Water, Air, and Soil Pollution 186, 351-363.

Dietz, M.E., Clausen, J.C., 2005. A field evaluation of rain garden flow and pollutant treatment. Water, Air, and Soil Pollution 167, 123-138.

Dietz, M.E., Clausen, J.C., 2006. Saturation to improve pollutant retention in a rain garden. Environmental Science & Technology 40, 1335-1340.

Donnelly, J.R., Shane, J.B., 1986. Forest ecosystem responses to artificially induced soil compaction. I. Soil physical properties and tree diameter growth. Canadian Journal of Forest Research 16, 750-754.

Endreny, T.A., 2005. Land use and land cover effects on runoff processes: Urban and suburban development. Encyclopedia of hydrological sciences.

Entry, J.A., Reeves, D.W., Mudd, E., Lee, W.J., Guertal, E., Raper, R.L., 1996. Influence of compaction from wheel traffic and tillage on arbuscular mycorrhizae infection and nutrient uptake by Zea mays. Plant and Soil 180, 139-146.

Escobedo, F.J., Kroeger, T., Wagner, J.E., 2011. Urban forests and pollution mitigation: Analyzing ecosystem services and disservices. Environmental Pollution 159, 2078-2087.

Faucette, L., Jordan, C., Risse, L., Cabrera, M., Coleman, D., West, L., 2005. Evaluation of stormwater from compost and conventional erosion control practices in construction activities. Journal of Soil and Water Conservation 60, 288-297.

Fite, K., Smiley, E.T., McIntyre, J., Wells, C.E., 2011. Evaluation of a soil decompaction and amendment process for urban trees. Arboriculture & Urban Forestry 37, 293-300.

Garcia-Fresca, B., Sharp Jr, J.M., 2005. Hydrogeologic considerations of urban development: Urban-induced recharge. Reviews in Engineering Geology 16, 123-136.

George, K., Ziska, L.H., Bunce, J.A., Quebedeaux, B., 2007. Elevated atmospheric CO2 concentration and temperature across an urban–rural transect. Atmospheric Environment 41, 7654-7665.

Gilman, E.F., Grabosky, J., 2004. Mulch and planting depth affect live oak (Quercus virginiana Mill.) establishment. Journal of Arboriculture 30, 311-317.

Godbold, D.L., Hoosbeek, M.R., Lukac, M., Cotrufo, M.F., Janssens, I.A., Ceulemans, R., Polle, A., Velthorst, E.J., Scarascia-Mugnozza, G., De Angelis, P., 2006. Mycorrhizal hyphal turnover as a dominant process for carbon input into soil organic matter. Plant and Soil 281, 15-24.

Grabosky, J., Bassuk, N., 1995. A new urban tree soil to safely increase rooting volumes under sidewalks. Journal of Arboriculture 21, 187-187.

Graves, W.R., 1994. Urban soil temperatures and their potential impact on tree growth. Journal of Arboriculture 20, 24-24.

Gregory, J.H., Dukes, M.D., Jones, P.H., Miller, G.L., 2006. Effect of urban soil compaction on infiltration rate. Journal of Soil and Water Conservation 61, 117-124.

Guo, J.C.Y., 2008. Volume-based imperviousness for storm water designs. Journal of Irrigation and Drainage Engineering-Asce 134, 193-196.

Gupta, S.C., Dowdy, R.H., Larson, W.E., 1977. Hydraulic and thermal properties of a sandy soil as influenced by incorporation of sewage sludge. Soil Science Society of America Journal 41, 601-605.

Halverson, H.G., Heisler, G.M., 1981. Soil temperatures under urban trees and asphalt. USDA Forest Service Research Paper.

Heath, J., Ayres, E., Possell, M., Bardgett, R.D., et al., 2005. Rising atmospheric CO2 reduces sequestration of root-derived soil carbon. Science 309, 1711-1713.

Heathwaite, L., Haygarth, P., Matthews, R., Preedy, N., Butler, P., 2005. Evaluating colloidal phosphorus delivery to surface waters from diffuse agricultural sources. Journal of Environmental Quality. 34, 287-298.

Herb, W.R., Janke, B., Mohseni, O., Stefan, H.G., 2008. Thermal pollution of streams by runoff from paved surfaces. Hydrological Processes 22, 987-999.

Hong, E., Seagren, E.A., Davis, A.P., 2006. Sustainable oil and grease removal from synthetic stormwater runoff using bench-scale bioretention studies. Water Environment Research 78, 141-155.

Hsieh, C.-H., Davis, A.P., 2005. Multiple-event study of bioretention for treatment of urban storm water runoff. Water Science & Technology 51, 177-181.

Idso, C.D., Idso, S.B., Balling Jr, R.C., 1998. The urban CO2 dome of Phoenix, Arizona. Physical Geography 19, 95-108.

Iles, J.K., Dosmann, M.S., 1999. Effect of organic and mineral mulches on soil properties and growth of Fairview Flame red maple trees. Journal of Arboriculture 25, 163-167.

Jackson, N., Wallace, J., 1999. Analysis of soil water dynamics in an agroforestry system based on detailed soil water records from time-domain reflectometry. Hydrology and Earth System Sciences Discussions 3, 517-527.

Jackson, N., Wallace, J., Ong, C., 2000. Tree pruning as a means of controlling water use in an agroforestry system in Kenya. Forest Ecology and Management 126, 133-148.

Jastrow, J.D., 1996. Soil aggregate formation and the accrual of particulate and mineral-associated organic matter. Soil Biology and Biochemistry 28, 665-676.

Jim, C., 1993. Soil compaction as a constraint to tree growth in tropical & subtropical urban habitats. Environmental Conservation 20, 35-49.

Jim, C., 1998. Urban soil characteristics and limitations for landscape planting in Hong Kong. Landscape and Urban Planning 40, 235-249.

Johnson, M.S., Lehmann, J., 2006. Double-funneling of trees: Stemflow and root-induced preferential flow. Ecoscience 13, 324-333.

Jones, M.P., Hunt, W.F., 2009. Bioretention impact on runoff temperature in trout sensitive waters. Journal of Environmental Engineering 135, 577-585.

Jones, M.P., Hunt, W.F., 2010. Effect of storm-water wetlands and wet ponds on runoff temperature in trout sensitive waters. Journal of Irrigation and Drainage Engineering 136, 656-661.

Jones, M.P., Hunt, W.F., Winston, R.J., 2012. Effect of urban catchment composition on runoff temperature. Journal of Environmental Engineering 138, 1231-1236.

Jurskis, V., 2005. Eucalypt decline in Australia, and a general concept of tree decline and dieback. Forest Ecology and Management 215, 1-20.

Klein, R.D., 1979. Urbanization and stream quality impairment. Journal of the American Water Resources Association 15, 948-963.

Koenker, K.M., 2002. User preference for trail surface material, Department of Landscape Architecture, University of Manitoba, Winnipeg, Canada

Komatsu, H., Katayama, A., Hirose, S., Kume, A., Higashi, N., Ogawa, S., Otsuki, K., 2007. Reduction in soil water availability and tree transpiration in a forest with pedestrian trampling. Agricultural and Forest Meteorology 146, 107-114.

Kozlowski, T., 1999. Soil compaction and growth of woody plants. Scandinavian Journal of Forest Research 14, 596-619.

Kuhns, M., Garrett, H., Teskey, R., Hinckley, T., 1985. Root growth of black walnut trees related to soil temperature, soil water potential, and leaf water potential. Forest Science 31, 617-629.

Layman, R., Day, S., Harris, J., Daniels, W., Wiseman, P., 2009. Rehabilitation of severely compacted urban soil to optimize tree establishment and growth. II International Conference on Landscape and Urban Horticulture 881, pp. 505-509.

LeBlanc, R.T., Brown, R.D., FitzGibbon, J.E., 1997. Modeling the effects of land use change on the water temperature in unregulated urban streams. Journal of Environmental Management 49, 445-469.

Lerner, D.N., 2002. Identifying and quantifying urban recharge: A review. Hydrogeology Journal 10, 143-152.

Lichter, J.M., Lindsey, P.A., 1994. The use of surface treatments for the prevention of soil compaction during site construction. Journal of Arboriculture 20, 205-205.

Lukac, M., Calfapietra, C., Godbold, D.L., 2003. Production, turnover and mycorrhizal colonization of root systems of three Populus species grown under elevated CO2 (POPFACE). Global Change Biology 9, 838-848.

Makepeace, D.K., Smith, D.W., Stanley, S.J., 1995. Urban stormwater quality: summary of contaminant data. Critical Reviews in Environmental Science and Technology 25, 93-139.

Matamala, R., Gonzalez-Meler, M.A., Jastrow, J.D., Norby, R.J., Schlesinger, W.H., 2003. Impacts of fine root turnover on forest NPP and soil C sequestration potential. Science 302, 1385-1387.

Materechera, S., Dexter, A., Alston, A., 1991. Penetration of very strong soils by seedling roots of different plant species. Plant and Soil 135, 31-41.

McPherson, E.G., Simpson, J.R., Xiao, Q., Wu, C., 2011. Million trees Los Angeles canopy cover and benefit assessment. Landscape and Urban Planning 99, 40-50.

Mitchell, A., Ellsworth, T., Meek, B., 1995. Effect of root systems on preferential flow in swelling soil. Communications in Soil Science & Plant Analysis 26, 2655-2666.

Morin, J., Benyamini, Y., 1977. Rainfall infiltration into bare soils. Water Resources Research 13, 813-817.

Moscrip, A.L., Montgomery, D.R., 1997. Urbanization, flood frequency, and salmon abundance in Puget lowland streams. Journal of the American Water Resources Association 33, 1289-1297.

Neller, R., 1988. A comparison of channel erosion in small urban and rural catchments, Armidale, New South Wales. Earth Surface Processes and Landforms 13, 1-7.

Oades, J.M., 1993. The role of biology in the formation, stabilization and degradation of soil structure. Geoderma 56, 377-400.

Oliveira, M., Merwin, I., 2001. Soil physical conditions in a New York orchard after eight years under different groundcover management systems. Plant and Soil 234, 233-237.

Pan, E., Bassuk, N., 1985. Effects of soil type and compaction on the growth of Ailanthus altissima seedlings. Journal of Environmental Horticulture 2, 158-162.

Park, S.-J., Cheng, Z., Yang, H., Morris, E.E., Sutherland, M., Gardener, B.B.M., Grewal, P.S., 2010. Differences in soil chemical properties with distance to roads and age of development in urban areas. Urban Ecosystems 13, 483-497.

Parks, O.W., 2012. Effect of water temperature on cohesive soil erosion, Biological Systems Engineering. Virginia Tech, Blacksburg, VA, p. 61.

Patterson, J.C., 1977. Soil compaction—effects on urban vegetation. Journal of Arboriculture 3.

Pepper, P., E.; , McPherson, G., Simpson, J., Gardner, S., Vargas, K., Xiao, Q., 2007. New York City, New York Municipal Forest Resource Analysis. Web.

Pitt, R., Chen, S.-E., Clark, S.E., Swenson, J., Ong, C.K., 2008. Compaction's impacts on urban storm-water infiltration. Journal of Irrigation and Drainage Engineering 134, 652-658.

Poland, T.M., McCullough, D.G., 2006. Emerald ash borer: Invasion of the urban forest and the threat to North America's Ash resource. Journal of Forestry 104, 118-124.

Pouyat, R.V., Yesilonis, I.D., Nowak, D.J., 2006. Carbon Storage by Urban Soils in the United States. Journal of Environmental Quality 35, 1566-1575.

Price, K., Jackson, C.R., Parker, A.J., 2010. Variation of surficial soil hydraulic properties across land uses in the southern Blue Ridge Mountains, North Carolina, USA. Journal of Hydrology 383, 256-268.

Randrup, T.B., Dralle, K., 1997. Influence of planning and design on soil compaction in construction sites. Landscape and Urban Planning 38, 87-92.

Ray, A.B., Selvakumar, A., Tafuri, A.N., 2006. Removal of selected pollutants from aqueous media by hardwood mulch. Journal of Hazardous Materials 136, 213-218.

Rees, W.E., 1997. Urban ecosystems: The human dimension. Urban Ecosystems 1, 63-75.

Rivenshield, A., Bassuk, N.L., 2007. Using organic amendments to decrease bulk density and increase macroporosity in compacted soils. Arboriculture and Urban Forestry 33, 140.

Roy, S., Byrne, J., Pickering, C., 2012. A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones. Urban Forestry & Urban Greening 11, 351-363.

Rutter, A., Kershaw, K., Robins, P., Morton, A., 1972. A predictive model of rainfall interception in forests, 1. Derivation of the model from observations in a plantation of Corsican pine. Agricultural Meteorology 9, 367-384.

Sahin, V., Hall, M.J., 1996. The effects of afforestation and deforestation on water yields. Journal of Hydrology 178, 293-309.

Scharenbroch, B.C., 2009. A meta-analysis of studies published in Arboriculture & Urban Forestry relating to organic materials and impacts on soil, tree, and environmental properties. Arboriculture & Urban Forestry 35, 221-231.

Scharenbroch, B.C., Lloyd, J.E., Johnson-Maynard, J.L., 2005. Distinguishing urban soils with physical, chemical, and biological properties. Pedobiologia 49, 283-296.

Seto, K.C., Güneralp, B., Hutyra, L.R., 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proceedings of the National Academy of Sciences 109, 16083-16088.

Shuster, W., Bonta, J., Thurston, H., Warnemuende, E., Smith, D., 2005. Impacts of impervious surface on watershed hydrology: A review. Urban Water Journal 2, 263-275.

Sjöman, J.D., Gill, S.E., 2013. Residential runoff – The role of spatial density and surface cover, with a case study in the Höjeå river catchment, southern Sweden. Urban Forestry & Urban Greening.

Skroch, W., Powell, M., Bilderback, T., Henry, P., 1992. Mulches: Durability, aesthetic value, weed control, and temperature. Journal of Environmental Horticulture 10, 43-45.

Sloan, J.J., Ampim, P.A., Basta, N.T., Scott, R., 2012. Addressing the need for soil blends and amendments for the highly modified urban landscape. Soil Science Society of America Journal 76, 1133-1141.

Smiley, E.T., Calfee, L., Fraedrich, B.R., Smiley, E.J., 2006. Comparison of structural and noncompacted soils for trees surrounded by pavement. Arboriculture and Urban Forestry 32, 164.

Solecki, W.D., Rosenzweig, C., Parshall, L., Pope, G., Clark, M., Cox, J., Wiencke, M., 2005. Mitigation of the heat island effect in urban New Jersey. Global Environmental Change Part B: Environmental Hazards 6, 39-49.

Stephens, D.B., Miller, M., Moore, S.J., Umstot, T., Salvato, D.J., 2012. Decentralized groundwater recharge systems using roofwater and stormwater runoff. Journal of the American Water Resources Association.

Stepniewski, W., Ball, B., Soane, B., Ouwerkerk, C.v., 1994. Effects of compaction on soil aeration properties, in: Soane, B.D., Ouwerkerk, C.v. (Eds.), Soil compaction in crop production. Elsevier Science Publishers, Amsterdam, Netherlands, pp. 167-189.

Throop, H., Archer, S., Monger, H.C., Waltman, S., 2012. When bulk density methods matter: Implications for estimating soil organic carbon pools in rocky soils. Journal of Arid Environments 77, 66-71.

Tiessen, H., Cuevas, E., Chacon, P., 1994. The role of soil organic matter in sustaining soil fertility. Nature 371, 783-785.

Tisdall, J., Oades, J.M., 1982. Organic matter and water-stable aggregates in soils. Journal of Soil Science 33, 141-163.

Townsend-Small, A., Pataki, D.E., Liu, H., Li, Z., Wu, Q., Thomas, B., 2013. Increasing summer river discharge in southern California, USA, linked to urbanization. Geophysical Research Letters 40, 4643-4647.

United Nations, Department of Economic and Social Affairs, Population Division, 2012. World Urbanization Prospects, the 2011 Revision. http://esa.un.org/unup/. Apr 10, 2013.

USEPA, Trees and Vegetation | Heat Island Effect | US EPA. http://www.epa.gov/heatisland/mitigation/trees.htm. June 14, 2014.

USEPA, 2004. National water quality inventory: Report to Congress. Environmental Protection Agency.

Van Buren, M.A., Watt, W.E., Marsalek, J., Anderson, B.C., 2000. Thermal enhancement of stormwater runoff by paved surfaces. Water Research 34, 1359-1371.

Wang, J., Endreny, T.A., Nowak, D.J., 2008. Mechanistic simulation of tree effects in an urban water balance model. Journal of the American Water Resources Association 44, 75-85.

Ware, G., 1990. Constraints to tree growth imposed by urban soil alkalinity. Journal of Arboriculture 16, 35-38.

Watson, G., Kelsey, P., Woodtli, K., 1996. Replacing soil in the root zone of mature trees for better growth. Journal of Arboriculture 22, 167-173.

Watson, G.W., 2002. Soil replacement: Long-term results. Journal of Arboriculture 28, 229-230.

Winston, R., Hunt, W., Lord, W., 2011. Thermal mitigation of urban storm water by level spreader–vegetative filter strips. Journal of Environmental Engineering 137, 707-716.

Woltemade, C.J., 2010. Impact of residential soil disturbance on infiltration rate and stormwater runoff. Journal of the American Water Resources Association 46, 700-711.

Xiao, Q., McPherson, E.G., 2002. Rainfall interception by Santa Monica's municipal urban forest. Urban Ecosystems 6, 291-302.

Xiao, Q., McPherson, E.G., 2011. Performance of engineered soil and trees in a parking lot bioswale. Urban Water Journal 8, 241-253.

Yunusa, I., Mele, P., Rab, M., Schefe, C., Beverly, C., 2002. Priming of soil structural and hydrological properties by native woody species, annual crops, and a permanent pasture. Soil Research 40, 207-219.

Zhang, B.A., Xie, G.D., Zhang, C.Q., Zhang, J., 2012. The economic benefits of rainwater-runoff reduction by urban green spaces: A case study in Beijing, China. Journal of Environmental Management 100, 65-71.

Zhang, Z., Rengel, Z., Liaghati, T., Antoniette, T., Meney, K., 2011. Influence of plant species and submerged zone with carbon addition on nutrient removal in stormwater biofilter. Ecological Engineering 37, 1833-1841.

Zinger, Y., Blecken, G.-T., Fletcher, T.D., Viklander, M., Deletić, A., 2013. Optimising nitrogen removal in existing stormwater biofilters: Benefits and tradeoffs of a retrofitted saturated zone. Ecological Engineering 51, 75-82.

Zisa, R.P., Halverson, H.G., Stout, B.B., 1980. Establishment and early growth of conifers on compact soils in urban areas. USDA Forest Service Research Paper.

Ziska, L.H., Bunce, J.A., Goins, E.W., 2004. Characterization of an urban-rural CO2/temperature gradient and associated changes in initial plant productivity during secondary succession. Oecologia 139, 454-458.

Chapter 3: Influence of landscape mulches on runoff generation from soil before and after simulated traffic

Abstract

Growth of urban populations has created large volumes of non-point source water pollution from urban stormwater runoff. Urban stormwater runoff occurs much faster and in higher volumes than runoff from natural or rural areas due to the presence of impervious surfaces; its increased speed and volume can cause erosion and degrade downstream water quality. As urban areas grow, the few open soils are needed to support greenspace as well as for use by people for recreation and movement within the city. Soils that are trafficked can become compacted and lose porosity, effectively acting like impervious surfaces and contributing to stormwater management costs of localities. Ornamental mulch materials may play a role in preventing or slowing runoff from soils in urban areas that are likely to become compacted by pedestrian or vehicle traffic. Simulated rainfall was used to examine 7 different mulches for their ability to prevent erosion and compaction, store precipitation, and slow runoff, using bare soil as a control. Runoff from wood chips increased by only 0.19 ml/s after traffic while runoff from bare soil and marble gravel with geotextile increased by 2.28 and 2.56 ml/s, respectively. Bare soil produced 460% more total suspended solids than mulches before compaction, and 265% more after compaction. Mulches can be an effective tool for mitigating runoff from soil surfaces, but their effectiveness depends on the type and whether or not they receive traffic.

Key words: ornamental mulch, rain simulation, stormwater runoff, urban soil,

Introduction

The proportion of the human population residing in urban areas is increasing globally (United Nations, 2012). Global urban land area is expected to triple during the period of 2000-2030, an increase of 1.2 million km^2 (Seto et al., 2012). The higher percentage of impervious surfaces covering soil in urban lands relative to rural areas drastically changes the local hydrologic cycle (Shuster et al., 2005) resulting in decreased base flows (Klein, 1979) but also higher peak flows and increased total runoff at the expense of soil water storage (Booth, 1991), increased flood frequency (Moscrip and Montgomery, 1997), and degraded water quality (Klein, 1979). In addition, increased overall flow volume and decreased minimum size of runoff-producing events in urban catchments results in higher rates of erosion in urban streams relative to rural streams (Neller, 1988). This erosion, combined with transport of sediment suspended in urban runoff to waterways (Fulcher, 1994; Makepeace et al., 1995), ecologically degrades receiving water bodies by increasing nutrient delivery, especially phosphorous (Heathwaite et al., 2005), and other contaminants (Bilotta and Brazier, 2008). Consequently there is considerable interest in reducing both the amount of urban runoff as well as reducing sediment concentrations in runoff.

Considerable amounts of urban runoff come from impervious surfaces and much of this runoff contains suspended sediment and other contaminants (Arnold Jr. and Gibbons, 1996; Makepeace et al., 1995). However, not all runoff is generated from impervious surfaces. Open soil (i.e., all areas that are not sealed by impervious surfaces) also contributes to runoff from urban areas, and this contribution may be considerable, as infiltration rates of urban soil are greatly reduced due to compaction from development (Gregory et al., 2006; Pitt et al., 2008). Soil areas adjoining impervious surfaces such as sidewalks and streets frequently get overflow traffic from the impervious surfaces as pedestrians tend to create shortcuts through corners and vehicles ride over pavement edges. Such areas are of particular concern for water quality as they are often compacted, do not drain well, may be devoid of vegetation, and may contribute to ponding or runoff depending on slope.

Unpaved soils in urban areas are managed in a variety of ways. Some are on steep areas that are minimally managed, some are in parks and in residential landscapes, and others occur in small patches such as near street tree plantings or in stormwater best management practices (BMPs). Some of these unsealed soils are covered with mulch, usually for aesthetics, tree protection, weed reduction, and/or moisture conservation purposes. However, mulches also have the ability to intercept applied water and prevent it from reaching the soil (Gilman and Grabosky, 2004), reduce erosion (Adekalu et al., 2006), and affect soil surface properties (Jordán et al., 2010), and consequently merit more investigation in the context of stormwater management.

Mulches have been widely studied for their aesthetic qualities and durability (e.g. Skroch et al., 1992), weed reduction ability (e.g. Billeaud and Zajicek, 1989), nutrient and organic matter inputs (e.g. Atucha et al., 2011), applicability for erosion control in agriculture (e.g. Adekalu et al., 2006), and their ability to alter soil moisture regimes (e.g. Iles and Dosmann, 1999) (see Chalker-Scott, 2007 for review). Mulches also have the ability to reduce compaction (e.g. Donnelly and Shane, 1986; Lichter and Lindsey, 1994), but this and other characteristics related to stormwater mitigation have not been studied as extensively as other aspects. Organic mulches are consistently specified as a top layer in bioinfiltration systems (Davis et al., 2009) and are able to adsorb contaminants, such as oil and grease, from stormwater (Hong et al., 2006). Use of woodchips as a thin mulch was effective as an erosion control measure during construction on steep slopes (Buchanan, 2002). Mulching with various composts also resulted in less erosion and nutrient loss than hydroseeding on hillsides (Faucette et al., 2005). In agricultural settings, organic mulch has been shown to slow runoff with increasing mulch rate (Jordán et al., 2010). However, agricultural mulches such as wheat straw and other crop residues have different physical properties than typical ornamental landscape mulches. The influences of various common landscape mulches outside of bioinfiltration systems on stormwater quantity and quality have received little or no attention.

Urban environments are also subject to intense people-pressures which may influence the effects of any soil surface coverings such as landscape mulch. The ability of mulches to retain runoff-slowing properties after traffic and to protect the underlying soil from foot-traffic-induced damage is unknown. The influence of such materials on hydrologic properties of urban soil is of interest because portions of the urban landscape not intended for foot traffic often become shortcuts, resulting in compact soil and increased runoff. Ornamental mulches may be used in these areas to prevent compaction and store precipitation, reducing the effect of the compacted soil. Regardless of whether the soil is trafficked, however, surface treatment of open soil surface areas likely has a significant effect on the quality and quantity of runoff generated. There are few estimates of the contribution of pervious areas to runoff generation or of the proportion of nonimpervious urban land that is not directly covered in vegetation. Berthier et al. (2004) determined that 14% of runoff in a small catchment in Rezé, France was from soil areas, but the proportion of that area that might be managed in mulch is unknown. Nonetheless, determining the effect of common surface treatments on local hydrology could contribute to the development of best management practices for stormwater mitigation from this portion of the urban landscape.

To assess the impact of different soil surface treatments on runoff generation and sediment transport, we examined the runoff generated by commonly used landscape mulches and bare soil under simulated rainfall both before and after trafficking. Our specific objectives were to:

1. Determine to what degree common landscape mulch types at typical application rates reduce runoff and sediment transport, especially compared with bare soil.
2. Evaluate whether these mulches prevent soil compaction from trafficking and whether trafficking alters their ability to mitigate runoff.
3. Determine if recommendations can be made concerning the stormwater management value of a given mulch type in a particular situation.

Methods

Location

Study plots were installed at the Virginia Tech Urban Horticulture Center in Blacksburg, Virginia at 37.218834°N, -80.463503°W on a site maintained for 5-10 years with mowed turfgrass on slopes ranging from 2.5% to 8.9%. Site soil is a Groseclose loam (fine, mixed, semiactive, mesic Typic Hapludults) weathered from limestone, shale, siltstone, and sandstone residuum.

Experimental design

The study was a before-after-control-impact (Smith, 2006) within a randomized block design, with 6 blocks and 8 treatments for a total of 48 experimental units. Runoff production and other variables were measured before and after compaction on all plots. Slopes within blocks varied by <2%, with the steepest experimental unit having a slope of 8.9% and the least steep with a slope of 2.4%. Blocks were placed perpendicular to the predominant slope on the site.

Plot installation

Existing vegetation at the site was killed by tilling surface soil which additionally provided a smooth and easily workable surface for plot installation. Vegetation that survived tillage was killed with glyphosate (*N*-(Phosphonomethyl) glycine) and 2,4-D (2,4-Dichlorophenoxyacetic acid). Circular 1 m^2 plots were installed on July 23, 2013 and graded individually to maintain a difference in slopes within blocks of less than 2%. The most level block had slopes ranging from 2.4 to 4.3%. The steepest block had slopes ranging between 7.0 and 8.9%. Plots were spaced 0.4 m apart within blocks, and blocks were spaced 1.5 m apart. Plots were edged with 13-cm tall flexible black plastic landscape border (Suncast EcoEdge, Batavia, IL), with approximately 8 cm buried below the soil surface to prevent subsurface flow out of the plot, and approximately 5 cm above the surface to contain the mulch treatment. An opening 25.4-cm wide was left at the lowest point in the plot edge to allow for runoff collection. Weeds within the study area were killed with glyphosate as needed from installation until conclusion of the experiment.

Surface treatments

Eight common landscape surface covers were studied. Using bare soil as a control, the other seven treatments were hardwood bark mulch (American Mulch and More, Christiansburg, VA), white pine (*Pinus strobus*) woodchips (manufactured on site using a Bandit model 200 chipper (Bandit Industries, Inc., Remus, MI)), slash pine (*Pinus elliotii*) pine straw (from a local home supply store), marble rock (American Mulch and More) underlain with geotextile, pea gravel (American Mulch and More), also with geotextile, marble rock without geotextile, and pea gravel without geotextile. Particle size ranges of each mulch are provided in Table 3.1. The pea gravel consisted of mostly flat gravels with rounded edges, and the marble rock was larger and much more angular. The geotextile was black, nonwoven polyester fabric approximately 0.5 mm thick (Sta-Green, Calhoun, GA) and was held in place with three wire ground staples. All mulch treatments were installed to a uniform depth of approximately 8 cm, approximating the typical 7.5-10 cm depth used in commercially constructed landscape beds.

Table 3.1. Size ranges of mulches applied to experimental units. Maximum and minimum particle dimensions from a 0.5 L subsample of each mulch type are given. Mulches other than pine straw also contained particles smaller than 0.2 cm that were not quantified.

Mulch type	Maximum size			Minimum size		
	L (cm)	W (cm)	H (cm)	L (cm)	W (cm)	H (cm)
Pine straw	26	0.2	0.2	21	0.2	0.2
Wood chips	2	1.3	0.5	<0.2	<0.2	<0.2
Shredded bark	9	3	1.5	<0.2	<0.2	<0.2
Pea gravel	2.5	1.4	0.5	<0.2	<0.2	<0.2
Marble rock	5.5	4	3.5	<0.2	<0.2	<0.2

Rainfall simulation

Rainfall was simulated on the experimental units with a Tlaloc 3000 Rainfall Simulator (2 m x 2 m; Joern's, Inc., West Lafayette, IN, 47906) before and after a compaction treatment, in order to measure the ability of various mulch types to prevent the formation of runoff in trafficked and non-trafficked areas. A downward facing sprinkler head with a rotating action, elevated 3.3 m above the plots, was used to simulate rainfall, one experimental unit at a time. Water pressure varied between 75.8 kPa and 89.6 kPa. Rainfall was timed to the nearest 5 s from when the simulator was turned on until 200 ml of runoff was collected, at which point the simulator was turned off. Storm duration, total precipitation, and rainfall rates ranged from 22.33 min to 1.83 min, 39.0 mm to 3.9 mm, and 197.5 mm/hr to 97.7 mm/hr with an average rate of 132.2 mm/hr, respectively. Total water applied was determined from an average of four Tru-Check® (Edwards Manufacturing Co., Albert Lea, MN, 56007) rain gauges positioned just outside the plot borders. Plots were isolated by a plastic curtain so that water would not overspray onto adjacent plots during simulation (Figure 3.1). In addition, natural rainfall data throughout the study period were obtained from a weather station located approximately 300 m from the site.

Figure 3.1. Plastic sheeting was used to isolate experimental units during rainfall simulation and shield adjacent plots from overspray. The sheeting also piped excess water out of the work area.

Soil moisture

Volumetric soil moisture at 0-10 cm depth was measured at each plot center prior to each rainfall simulation and the compaction treatment with a Fieldscout TDR 100 soil moisture meter (Spectrum Technologies, Inc., Aurora, IL). Plots experienced natural rainfall throughout the study. After the final rainfall simulation on May 8th, 2014, plots were allowed to experience wetting and drying cycles through natural rain. Two rain events occurred on June 4th and 5th totaling 22.8 mm, and soil moisture was measured under each mulch type on June 7th 2014.

Runoff collection

Runoff was collected in troughs, manufactured from 1 mm thick aluminum sheet metal, that funneled water through a 55-cm garden hose to a collection bottle (Figure 3.2). A stopwatch was used to determine time from the beginning of rainfall until runoff first entered the collection bottle, and until 200 ml was collected, at which point the simulation and time were stopped. Runoff was stored in collection bottles and held in a cooler at 4.4°C until being processed for total suspended solids concentration using a filtration method (American Public Health Association, 1995).

Data processing

Rain rates were calculated by taking the average reading from four rain gauges from each rain simulation and dividing by the duration of the storm, yielding a rain rate in mm/h for each individual simulation. Rain rates were used to determine the amount of water applied to each plot prior to runoff initiation (referred to as rainfall absorbed). Rain rates for simulations before and after the compaction treatment were statistically different at $p=0.005$, with a mean rate before compaction of 137 mm/hr and a mean rate after compaction of 127 mm/hr. Rain was stopped when 200 ml of runoff had been collected.

Compaction treatment

After the first rainfall simulation, a compaction treatment to simulate force applied by regular human foot traffic was applied to all plots. After the compaction treatment, the rainfall simulation and runoff collection procedure was repeated. Plots were compacted using a jumping-jack style compactor, model MTX70HD (Multiquip Carson, CA) operated at full speed, delivering 690 blows/min at 14.90 kN/blow. A plywood disk (38 mm thick) was placed on each plot to distribute the compactive force as evenly as possible (Figure 3.3). The area of the disk was 0.85 m^2 (slightly smaller than the plot to ensure that plot borders were not disturbed during compaction) therefore the applied pressure from each blow was 17.5 kPa. All plots had a volumetric water content at 0-10 cm depth of at least 25% before the compaction treatment (mean 32.0%, SE mean 0.73%, n=48). Bulk density was sampled with a core sampler (sleeve dimensions, 48.1 mm diameter by 50.3 mm tall) at 5-10 cm depth in the soil under the mulch material in the upper left (facing uphill) quadrant of the plots before compaction, and in the upper right quadrant of the plot after compaction. Holes left from core removal were filled with soil adjacent to the plot and mulch was replaced.

Figure 3.2. Runoff collection pan and bottle.

Figure 3.3. The compaction treatment was performed by running a jumping-jack style compactor over a 38 mm thick plywood disk on each plot. The disk was slightly smaller than the plot to avoid disturbing plot borders.

Statistical analysis

Statistical analyses were performed with Minitab 16 Statistical Software (Minitab, Inc., State College, PA). Two-sample t-tests were used to detect differences in rain rates, total suspended solids, runoff absorption, and runoff rates within mulch types before and after compaction. General Linear Models were used to determine effects of treatment, blocks, average rainfall intensity and soil moisture. Nine pre-planned contrasts of differences in time to runoff initiation, production of 200 ml runoff, and bulk density were tested: bare soil v. mulch; organic v. inorganic; geotextile v. no geotextile; marble rock v. pea gravel; wood chip v. bark; bark and wood chip v. pine straw. Contrasts were tested with SAS® Statistical Software version 9.3 (SAS Institute Inc., Cary, NC), specific p-values are reported.

Results and Discussion

Mulch interaction with rainfall before traffic

Mulches absorb rainfall before runoff initiation

Each treatment absorbed rainfall before runoff initiated in the plot (Figure 3.4). Although there were no differences between mulched plots and bare plots, among plots with gravel mulch, those without geotextile absorbed more rainfall than plots with geotextile (Table 3.2), i.e., runoff generation from non-geotextile plots took more time than geotextile plots. We applied mulches to depths of 8 cm, and our simulated rain storms were of very high intensity. Rainfall simulations before traffic applied intense rainfall that lasted a mean of 9 minutes and applied 20 mm of rainfall corresponding to the 10-yr 10-min return frequency storm for Blacksburg, VA. Plots absorbed a mean of 7.9 mm of rain before producing runoff. Smaller, less intense rain events might be absorbed by mulch coverings; Gilman and Grabosky (2004) saw interception of 6 mm of irrigation water by 15-cm deep mulches during small irrigation events, preventing wetting of the underlying soil. The lack of difference between precipitation absorbed by bare plots and by mulch plots is likely due to the consistently lower initial moisture condition of the bare plots (volumetric water content; bare mean 22%, SE 2.11; other mulch mean 33%, SE 0.62). Soil water status before rain events is known to be an important factor in runoff generation (Berthier et al., 2004).

Mulch type affects runoff rates

Unlike rainfall absorbed, average initial runoff rates varied considerably between mulches (Figure 3.5). Bare soil exhibited a higher average runoff rate than mulched soils, and inorganic mulches with geotextile produced faster runoff than those without it; pea gravel also had higher runoff rates than marble rock (Table3.2). These results suggest that a portion of the rainfall was running off of the geotextile directly, without ever reaching the soil surface. Effects on runoff rates from organic mulches were similar. Mulch extends the rainfall's path to the soil,

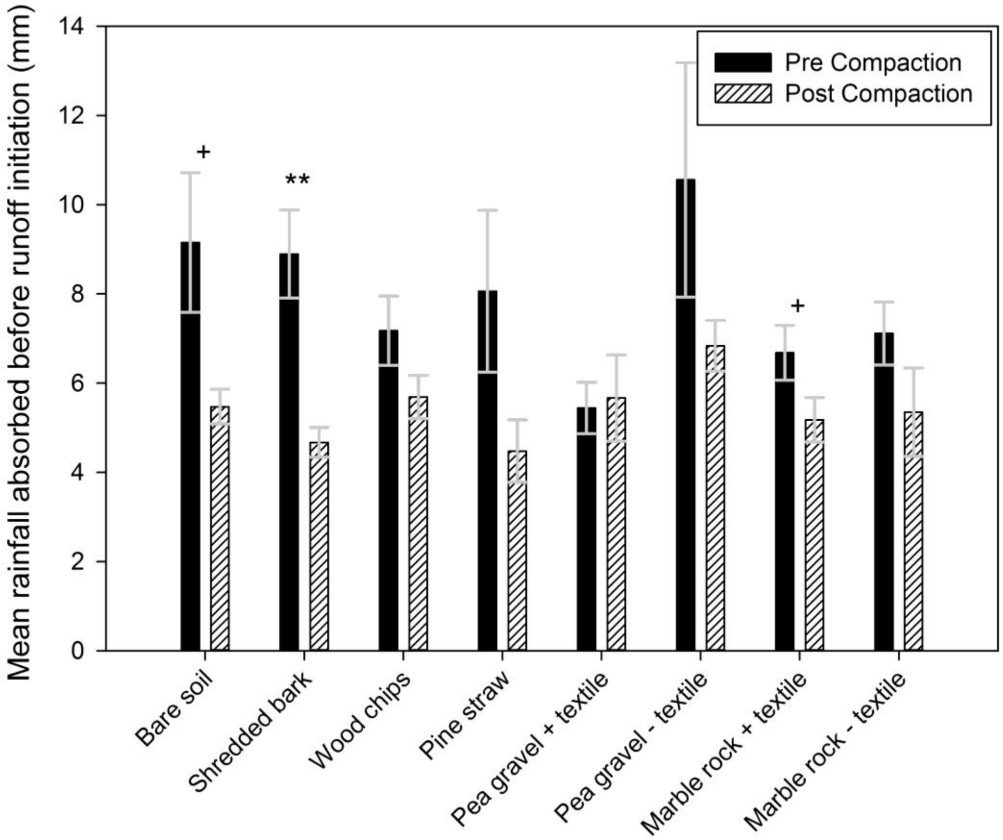

Figure 3.4. Mean rainfall absorbed by soil and surface cover before runoff initiated. Data are shown for rainfall simulations before and after compaction treatment. Differences before and after compaction significant at p<0.1, p<0.05, and p<0.01 indicated by +, *, and ** respectively. Mean rain rate 132 mm/h (standard error of mean = 1.89). Error bars represent standard errors of the means (n=6).

and makes flow across the surface more tortuous, resulting in slower runoff rates. Jordán et al. (2010) saw decreased runoff with increasing wheat straw mulch rates on agricultural soils in Spain. Because the matrix of pea gravel mulch is more dense than that of marble rock, it is surprising it had a faster runoff rate, especially considering the similar initial soil moisture between the two mulches. It is possible that the larger particles of the marble rock mulch altered the micro-topography of the soil surface more than the pea gravel, creating divots where ponding could occur (i.e., increased initial abstraction). This third dimension of tortuousness in the marble rock plots may explain the slower runoff rates compared to the pea gravel. Shredded bark and wood chip mulches have porous particles and a flat, long interlocking structure that provides higher surface area and causes these mulches to act more like a sponge than pine straw and the inorganic mulches. The materials themselves also differ, with inorganic mulches having no ability to absorb water into primary particles, and pine straw having a waxy cuticle, while the wood chip and bark mulches are more able to absorb water, and likely have more friction to resist flow.

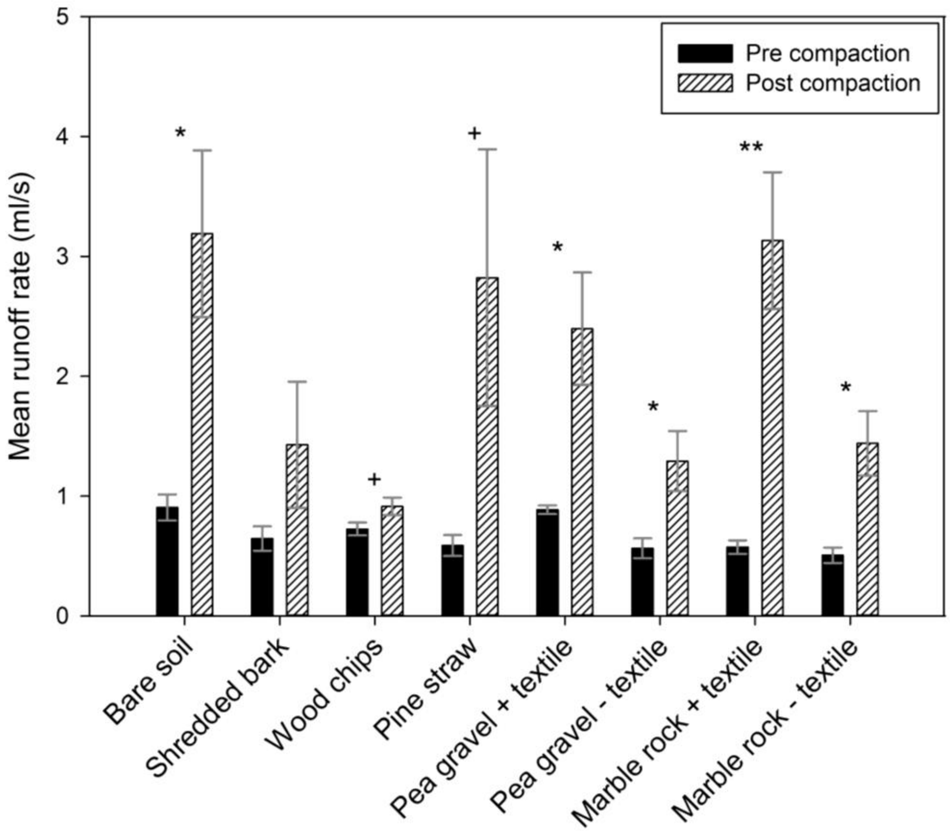

Figure 3.5. Mean runoff rates from plots before and after compaction treatment. Differences of before and after compaction significant at p<0.1, p<0.05, and p<0.01 indicated by +, *, and ** respectively. Mean rain rate of 132 mm/h (standard error of mean = 1.89). Bars represent standard errors of the means (n=6).

Total suspended solids is reduced by mulching

Total suspended solids (TSS) concentration in runoff from mulch plots was five times higher from bare plots than from mulched plots (Figure 3.6). Mulches of organic material also produced significantly less TSS in runoff than inorganic mulches. It should be pointed out that there is an unknown base level of TSS (likely around 0.5 g/l) that came off of all plots in our study due to disturbance when installing the runoff collection trough. Mulches are known to be effective at reducing erosion because they prevent raindrops from impacting the soil, and slow runoff across the surface, reducing sheet erosion. Gravel and straw mulches 5 cm thick "essentially eliminated" erosion in a Texas study on an Austin clay soil, while significant erosion occurred from bare soil plots (Adams, 1966). Buchanan (2002) found 80% cover by raw wood chips, as typically produced from arboricultural activities (similar to woodchips used in our experiment), to prevent 86% of erosion on 55% slopes when compared to zero soil covering. Woodchips in the Buchanan study were spread thinly in order to ensure establishment of vegetation. Similarly, Adekalu et al. (2006) found that increasing areal coverage of bamboo leaf mulch reduced soil erosion on a 12% slope. Organic mulches seem to reduce erosion somewhat better than inorganics, perhaps because they are more able to absorb impact energy than inorganic mulches.

Mitigation of compaction by mulching

Mulches were expected to absorb some of the energy applied by traffic and prevent compactive force from being applied to the underlying soil. Soil bulk density at 5-10 cm depth differed before and after compaction in some cases, but not in others (Figure 3.7). High variance in pre-compaction bulk densities prevent conclusions from being drawn about the ability of shredded bark, wood chip and marble rock treatments to prevent compaction. Pine straw and both pea gravel treatments appear to be no more effective at preventing bulk density increase than bare soil. Due to the nature of soil, as the soil matrix becomes denser, increased effort is required to further increase the density. It appears that the compaction treatment we applied brought the soil to a consistent bulk density throughout the study area, ranging from about 1.4 to 1.5 g/cm^3. Other studies have found mulches to be effective at reducing compaction from vehicle traffic compared with bare soil, however compaction still occurred under mulches (Donnelly and Shane, 1986; Lichter and Lindsey, 1994). Mulches and gravel applied at a 15 and 10 cm thickness respectively, allowed a 5.6% increase in bulk density while bare ground allowed a

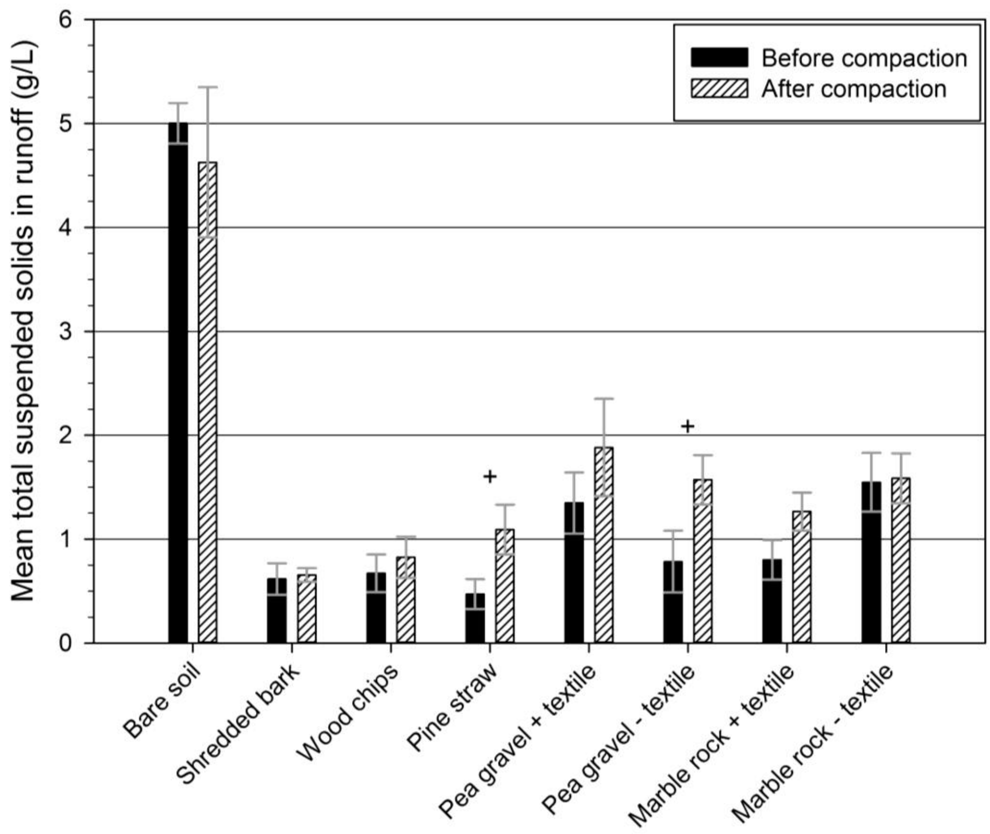

Figure 3.6. Mean total suspended solids (TSS) concentration of runoff collected under simulated rainfall from plots with 8 different surface cover types before and after compaction. Differences of before and after compaction means significant at p<0.1, p<0.05, and p<0.01 are indicated by +, *, and ** respectively. Mean rain rate of 132 mm/h (standard error of mean = 1.89). Bars represent standard errors of the means (n=6). For statistics see Table 3.2.

12.0% increase (Lichter and Lindsey, 1994). Lichter and Lindsey (1994) saw no difference in the ability to prevent compaction gravel with or without geotextile, while our data had variable starting points, it also appears that there was no effect of geotextile on bulk density. We did observe that the geotextile prevented intrusion of gravel into the soil during the simulated traffic, agreeing with the findings of Freeman et al. (2000).

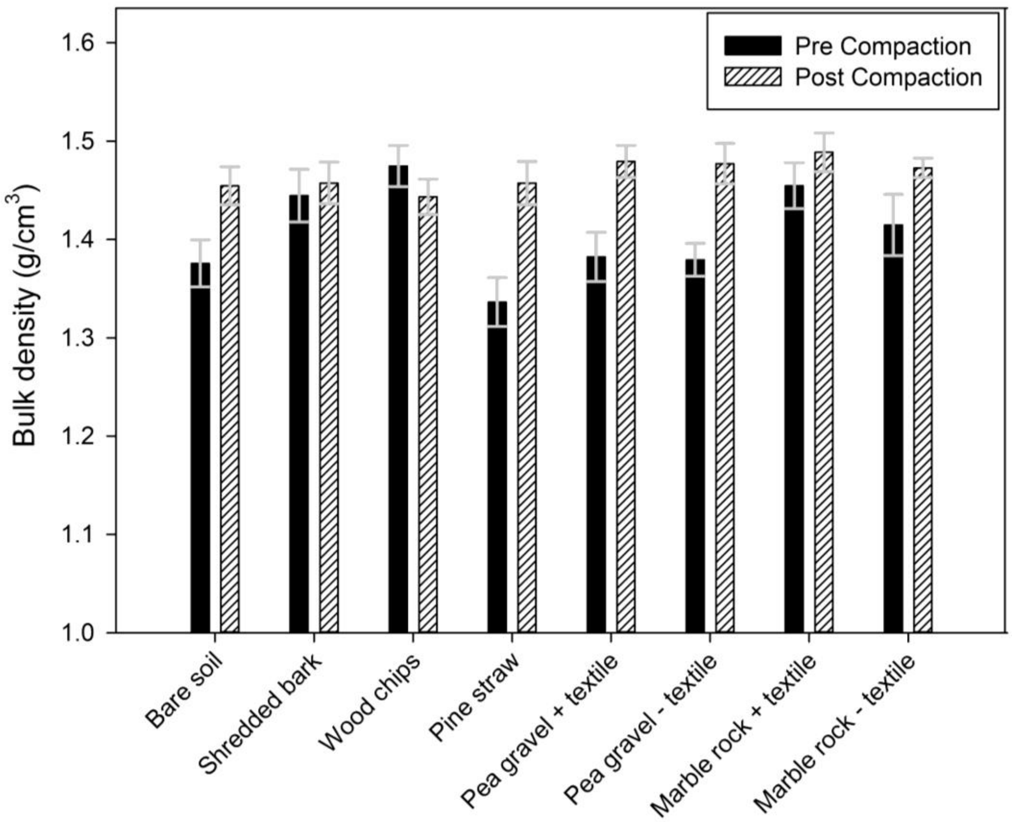

Figure 3.7. Mean soil bulk density at 5-10 cm depth before and after compaction treatment. Bars represent standard errors of the means (n=6).

Direct measurement of compaction via bulk density was inconclusive, possibly due to variable initial bulk density and because it does not capture changes to the soil surface that may result in sealing. Because compacted soil produces more runoff (Gregory et al., 2006), runoff rate and amount of rain absorbed before runoff initiation may be used as proxies for measurement of compaction and the resulting sealing of the soil surface. The mean runoff rate of mulched plots before compaction was 0.642 ml/s (S.E. 0.031) and the mean runoff rate after compaction was 1.92 ml/s (S.E. 0.23) these values differed significantly ($p<0.001$). Prior to compaction, the mean amount absorbed by mulched plots was 7.70 mm (S.E. 0.53) and the amount absorbed after compaction was 5.41 mm (S.E. 0.27), which were significantly different ($p<0.001$). These measurements are influenced by soil moisture as well as compaction level.

Mulch behavior changes after simulated traffic

Two different disturbances were expected from the traffic simulations. The simulation compacted the soil, and it also compacted the mulches. Because the mulch and soils act together in handling stormwater, response of runoff, suspended solids, soil moisture content, and rain absorption may be affected by either a change in soil, a change in soil moisture content, a change in mulch or changes in both soil and mulch.

Rain absorbed before runoff initiation

Compacted soil in the landscape may have very little pore space, and thus create runoff quite quickly. Mulching such soil areas with material that could intercept precipitation could reduce the volume of runoff as well as increase the amount needed to initiate runoff. Variability in the amount of rain absorbed by mulches and soil was reduced after compaction. Rain rate was not a significant covariate ($\alpha=0.1$) for rain absorbed when compared with pre-compaction data. Rain absorbed before runoff initiation was significantly reduced in plots with bare soil, shredded bark and marble rock with textile mulches (Figure 3.4). The amount of rain absorbed by all mulch treatments and bare soil after compaction was significantly less than before compaction ($p<0.001$). Differences due to the presence of geotextile from before compaction were absent in rain simulations post-compaction. This may perhaps be attributed to the large decrease after compaction in runoff absorbed by pea gravel without textile, implying that soil under this mulch became sealed during compaction.

Table 3.2. P-values of pre-planned contrasts for mean total suspended solids in runoff, rain absorbed by mulch and soil before initiation of runoff, runoff rate, change in runoff rate from before to after compaction, and moisture of soil under mulch after compaction and uniform wetting and drying. Simulated rainfall had a mean rain rate of 132 mm/h (standard error of mean = 1.89). Soil volumetric water content was measured on June 7, 2014, 2 days after 2 rain events totaling 22.8mm. Data are presented in Figures 3.1-3.5. P-values <0.05 are in bold.

	P- values							
	Total suspended solids		**Rain absorbed before runoff initiation**		**Runoff rate**		**Change in runoff rate**	**Soil volumetric water content**
Contrasts	Before	After	Before	After	Before	After		
Bare vs mulched	**<0.0001**	**<0.0001**	0.3005	0.9277	**0.0019**	**0.0265**	0.0724	**0.0002**
With geotextile vs without geotextile	0.6614	0.9897	**0.0384**	0.3115	**0.0120**	**0.0099**	**0.0237**	0.7017
Organic mulch vs inorganic mulch	**0.0017**	**0.0131**	0.5498	0.1130	0.7246	0.3865	0.3556	0.7630
Marble rock vs pea gravel	0.6010	0.4086	0.4003	0.1389	**0.0163**	0.3947	0.2259	0.7539
Wood chip vs bark	0.8511	0.7408	0.3533	0.2763	0.4496	0.4837	0.4154	**0.0366**
Bark &wood chip vs pine straw	0.4967	0.4307	0.9862	0.3848	0.2843	**0.0126**	**0.0081**	**0.0012**

Runoff rates

Compaction significantly increased runoff rates in all treatments except shredded bark (Figure 3.5). Rain rates were not significant covariates (α=0.1) for runoff rates when compared with pre-compaction data. Specifically, bare soil had a higher runoff rate after compaction than mulched treatments, just like before simulated traffic. Similar to pre compaction, inorganic mulches with geotextile had a higher mean runoff rate than those without geotextile. Unlike the pre-compaction rain simulations, runoff rates from pine straw plots were higher than those from shredded bark and woodchips (see Table 3.2 for p-values). Bamboo leaf mulch slowed runoff more as coverage increased in a study by Adekalu et al. (2006) suggesting that a longer flow path of water allows more time for infiltration. This may have also been the case in our study after compaction, as wood chips formed a denser mat than other mulches, requiring water to take a more tortuous path. It is also possible that wood chips continued to absorb water for the duration of the storm, contributing to decreased runoff rates.

Total suspended solids

For most mulch materials, compaction had little effect on TSS in runoff (Figure 3.6), although TSS concentration in runoff increased significantly after compaction in both pine straw (p=0.057) and pea gravel without textile (p=0.068) plots. Runoff from bare soil plots still had much higher TSS concentration than all mulched plots, and organic mulches still produced significantly lower TSS concentrations in runoff than inorganic mulches (Table 3.2). Among organic mulches, pine straw was the most visibly affected by compaction. The compaction treatment both broke up the pine straw particles and moved them down-slope, partially exposing the soil underneath, likely the reason for the increase in TSS. Pea gravel without textile was imbedded into the soil after the compaction treatment, diffusing the mulch-soil interface, and perhaps loosening some soil particles, increasing their chance of being eroded. Rain rate was not significant as a covariate (α=0.1) for TSS when compared with pre-compaction data. In contrast to the findings of Adekalu et al. (2006), who saw decreases in soil loss from mulched plots with higher compaction rates, we found little or no change in TSS production from most mulches, and an increase only from pine straw, due to movement of the mulch material by the simulated traffic.

Mulches that respond to rain similarly before and after traffic are likely useful in trafficked areas

If mulches are likely to receive pedestrian or vehicular traffic and are intended to decrease runoff rates from soil surfaces, mulches that are able to maintain their runoff-slowing characteristics when trafficked are better choices to maintain long term functionality. Mulches that decrease in their ability to slow runoff after traffic would not retain this function in trafficked areas. Before and after compaction runoff rates are compared to find the mulch that changed least from simulated traffic. Increase in runoff rate after compaction was least for wood chips (0.19 ml/s; SE mean 0.069), and greatest for marble rock with textile (2.56 ml/s; SE mean 0.59), which was similar to the increase from bare soil (2.28 ml/s; SE mean 0.69) and pine straw (2.24 ml/s; SE mean 1.09) (Figure 3.5). Although prior to compaction, there was no difference in the runoff rates among organic mulches, the magnitude of change in pine straw was significantly greater than bark and wood chip mulches. Pea gravel had higher runoff rates than marble rock before compaction, but afterward their rates were not different, and the magnitudes of the changes were also similar. Including geotextile under gravel mulches, however, does result in a larger change in runoff after being trafficked, and thus may be undesirable where slowing runoff is the goal. However, Freeman et al. (2000) point out that geotextile is valuable for preventing aggregate intrusion into subsoil, preventing trail rutting and improving drainage, thus keeping trail maintenance costs low. Use of geotextile may be more cost effective than slowing stormwater runoff for trails that need to be surfaced with gravel, such as those intended for biking. Hikers, however, have been shown to favor a wood chip trail surface (Koenker, 2002), and thus wood chips would be the logical choice for trails or potentially trafficked areas where foot traffic is dominant and the desire to slow runoff exists.

Moisture retention

Mulches held significantly more water after compaction than bare soil (Table 3.2), although pine straw was very similar to bare soil in its lack of ability to conserve soil moisture (Figure 3.8). Because moisture retention was measured after simulated traffic, the poor moisture retention of pine straw can be attributed to the particles being broken and moved around by the traffic simulation, leaving some soil exposed. Wood chips held significantly more moisture in the soil than bark mulch, and both held more than pine straw. The presence of geotextile had no effect on a mulches ability to conserve moisture, and no differences were seen between inorganic and organic mulches, nor between pea gravel and marble rock (Table 3.2). Iles and Dosmann (1999) saw differences in moisture conservation from 0.9-cm diameter pea gravel and 3.8-cm diameter river rock (approximately the same size disparity of pea gravel and marble rock used here), and attributed the lower moisture under the larger rock to larger pore size within the mulch. Two possibilities exist as to why we did not observe the same phenomenon: first, that our soil was compacted and diffusion of water was restricted compared to the non-compacted soil in their study, or second, that the near-white color of the marble rock resulted in lower temperatures than that of the brown pea gravel, balancing the effect of the larger pores.

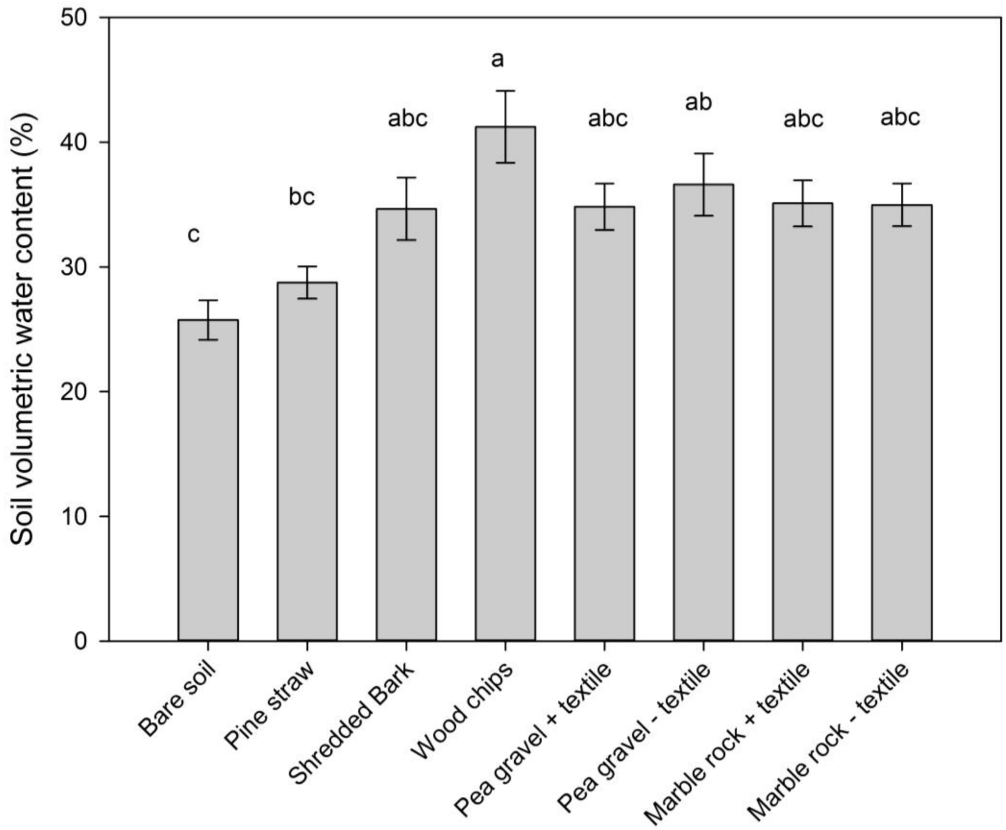

Figure 3.8. Mean soil volumetric water content 0-10 cm under different surface treatments 2 days after 2 rain events totaling 22.8 mm. Columns that do not share a letter are significantly different at α=0.05 using Tukey's HSD. Bars represent standard errors of the means (n=6).

Conclusion

Ornamental mulches, usually intended for aesthetics, weed control and soil moisture conservation, have a role in stormwater management on potentially trafficked urban soils. Runoff rate from soils can be slowed by wood chips, shredded bark, and gravel mulches without geotextile separating the mulch and soil. Wood chips commonly produced from arboricultural activities are most effective for slowing runoff among mulches tested, and trafficked gravels with geotextile are no more, if not less effective than trafficked bare soil. All mulches can reduce erosion, although durable organic mulches like shredded bark or wood chips are best, especially in trafficked areas. Pine straw is not effective for slowing runoff in potentially trafficked areas, as traffic will break and move it, exposing bare soil, leading to erosion during heavy rain. Any of the materials tested would slow stormwater in areas without traffic, as differences in runoff rates before traffic were small. Mulches are a tool that can directly contribute to dispersed approach to stormwater management, through their effect on runoff rate, and indirectly contribute through improving soil quality for growing large trees. Further research in an area with a very consistent initial bulk density is needed to determine if mulches can prevent compaction from traffic.

References

Adams, J.E. 1966. Influence of mulches on runoff, erosion, and soil moisture depletion. Soil Science Society of America Journal 30: 110-114. doi:10.2136/sssaj1966.03615995003000010036x.

Adekalu, K.O., D.A. Okunade and J.A. Osunbitan. 2006. Compaction and mulching effects on soil loss and runoff from two southwestern Nigeria agricultural soils. Geoderma 137: 226-230. doi:http://dx.doi.org/10.1016/j.geoderma.2006.08.012.

American Public Health Association. 1995. Solids. In: A. D. Eaton, L. S. Clesceri and A. E. Greenberg, editors, Standard methods for the examination of water and wastewater. APHA, Washington, DC. p. 53.

Arnold Jr., C.L. and C.J. Gibbons. 1996. Impervious surface coverage: the emergence of a key environmental indicator. Journal of the American Planning Association 62: 243-258.

Atucha, A., I.A. Merwin and M.G. Brown. 2011. Long-term effects of four groundcover management systems in an apple orchard. HortScience 46: 1176-1183.

Berthier, E., H. Andrieu and J.D. Creutin. 2004. The role of soil in the generation of urban runoff: development and evaluation of a 2D model. Journal of Hydrology 299: 252-266. doi:http://dx.doi.org/10.1016/j.jhydrol.2004.08.008.

Billeaud, L.A. and J.M. Zajicek. 1989. Influence of mulches on weed control, soil pH, soil nitrogen content, and growth of *Ligustrum japonicum*. Journal of Environmental Horticulture 7: 155-157.

Bilotta, G.S. and R.E. Brazier. 2008. Understanding the influence of suspended solids on water quality and aquatic biota. Water Research 42: 2849-2861. doi:http://dx.doi.org/10.1016/j.watres.2008.03.018.

Booth, D.B. 1991. Urbanization and the natural drainage system--impacts, solutions, and prognoses. The Northwest Environmental Journal 7, 93-118.

Buchanan, J. 2002. Wood chips as a soil cover for construction sites with steep slopes. Applied Engineering in Agriculture 18: 679-684.

Chalker-Scott, L. 2007. Impact of mulches on landscape plants and the environment-A review. Journal of Environmental Horticulture 25: 239.

Davis, A.P., W.F. Hunt, R.G. Traver and M. Clar. 2009. Bioretention technology: Overview of current practice and future needs. Journal of Environmental Engineering 135: 109-117.

Donnelly, J.R. and J.B. Shane. 1986. Forest ecosystem responses to artificially induced soil compaction. I. Soil physical properties and tree diameter growth. Canadian Journal of Forest Research 16: 750-754. doi:10.1139/x86-134.

Faucette, L., C. Jordan, L. Risse, M. Cabrera, D. Coleman and L. West. 2005. Evaluation of stormwater from compost and conventional erosion control practices in construction activities. Journal of Soil and Water Conservation 60: 288-297.

Freeman, E., J.E. Loehr and J.J. Bowders. 2000. Geotextile separators for hike and bike trail. Geotechnical Special Publication: 377-387.

Fulcher, G.A. 1994. Urban stormwater quality from a residential catchment. Science of The Total Environment 146–147: 535-542. doi:10.1016/0048-9697(94)90279-8.

Gilman, E.F. and J. Grabosky. 2004. Mulch and planting depth affect live oak (Quercus virginiana Mill.) establishment. Journal of Arboriculture 30: 311-317.

Gregory, J.H., M.D. Dukes, P.H. Jones and G.L. Miller. 2006. Effect of urban soil compaction on infiltration rate. Journal of Soil and Water Conservation 61: 117-124.

Heathwaite, L., P. Haygarth, R. Matthews, N. Preedy and P. Butler. 2005. Evaluating colloidal phosphorus delivery to surface waters from diffuse agricultural sources. Journal of Environmental Quality 34: 287-298. doi:10.2134/jeq2005.0287.

Hong, E., E.A. Seagren and A.P. Davis. 2006. Sustainable oil and grease removal from synthetic stormwater runoff using bench-scale bioretention studies. Water Environment Research 78: 141-155.

Iles, J.K. and M.S. Dosmann. 1999. Effect of organic and mineral mulches on soil properties and growth of Fairview Flame red maple trees. Journal of Arboriculture 25: 163-167.

Institute, S. SAS Version 9.3. SAS Institute Inc., Cary, NC, USA.

Jordán, A., L.M. Zavala and J. Gil. 2010. Effects of mulching on soil physical properties and runoff under semi-arid conditions in southern Spain. Catena 81: 77-85. doi:http://dx.doi.org/10.1016/j.catena.2010.01.007.

Klein, R.D. 1979. Urbanization and stream quality impairment. Journal of the American Water Resources Association 15: 948-963.

Koenker, K.M. 2002. User preference for trail surface material, Department of Landscape Architecture, University of Manitoba, Winnipeg, Canada.

Lichter, J.M. and P.A. Lindsey. 1994. The use of surface treatments for the prevention of soil compaction during site construction. Journal of Arboriculture 20: 205-205.

Makepeace, D.K., D.W. Smith and S.J. Stanley. 1995. Urban stormwater quality: summary of contaminant data. Critical Reviews in Environmental Science and Technology 25: 93-139.

Moscrip, A.L. and D.R. Montgomery. 1997. Urbanization, flood frequency, and salmon abundance in Puget lowland streams. Journal of the American Water Resources Association 33: 1289-1297.

Neller, R. 1988. A comparison of channel erosion in small urban and rural catchments, Armidale, New South Wales. Earth Surface Processes and Landforms 13: 1-7.

Pitt, R., S.-E. Chen, S.E. Clark, J. Swenson and C.K. Ong. 2008. Compaction's impacts on urban storm-water infiltration. Journal of Irrigation and Drainage Engineering 134: 652-658.

Seto, K.C., B. Güneralp and L.R. Hutyra. 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proceedings of the National Academy of Sciences 109: 16083-16088. doi:10.1073/pnas.1211658109.

Shuster, W., J. Bonta, H. Thurston, E. Warnemuende and D. Smith. 2005. Impacts of impervious surface on watershed hydrology: A review. Urban Water Journal 2: 263-275.

Skroch, W., M. Powell, T. Bilderback and P. Henry. 1992. Mulches: Durability, aesthetic value, weed control, and temperature. Journal of Environmental Horticulture 10: 43-45.

Smith, E.P. 2006. BACI Design. Encyclopedia of Environmetrics. John Wiley & Sons, Ltd.

United Nations. 2012. World Urbanization Prospects, the 2011 Revision. United Nations, Department of Economic and Social Affairs, Population Division.

Chapter 4: Soil rehabilitation for increased stormwater mitigation potential of developed landscapes

Abstract

Growth of urban populations has created large areas contributing to nonpoint source water pollution from urban stormwater runoff. Trees and soils aid in reducing the volume of urban stormwater runoff through interception and stemflow, sequestering would-be runoff in the soil. Due to soil degradation during land development, soils may be nearly as impervious as paved surfaces and growing long-lived, healthy trees can be challenging. This study of streetside tree planting areas in Arlington, Virginia, USA, examines a soil rehabilitation method that uses deep incorporation of compost, designed to decrease soil density and promote tree growth, water movement and soil carbon storage, and compares it to standard soil preparation practices in the city. Twenty-five plots were converted from paved surfaces and planted with 36 trees of three different species for this study. One year after installation, at 15-30 cm depth, bulk density was 13.3% lower, and macro-aggregate-associated carbon was 151% higher in rehabilitated plots than in controls, although there were no differences in total organic carbon. Cross-sectional area growth of trees during the first year after installation was also 77% higher. There were no differences in saturated or near saturated hydraulic conductivity, possibly due to the scale of measurement of saturated, and the identical topsoil used in construction of rehabilitated and control plots. Deep incorporation of compost may be a useful tool for dispersed approaches to urban stormwater management, by increasing tree growth during the first year after installation and increasing soil porosity.

Key words*: compost, hydraulic conductivity, soil carbon, tree establishment, urban forestry , urban soil*

Introduction

The proportion of the human population residing in urban areas is increasing globally (United Nations, 2012). At the same time, urban land area is expected to triple during the period of 2000-2030, increasing by 1.2 million km^2 (Seto et al., 2012). Increased impervious cover in urban lands compared to rural areas results in drastic changes to the local hydrologic cycle (Shuster et al., 2005) with not only decreased base flow in local streams (Klein, 1979) but also higher peak flows and greater total runoff with less water percolating into and being stored by soil (Booth, 1991). Local hydrology also changes through increased flood frequency (Moscrip and Montgomery, 1997), and declines in water quality (Klein, 1979) (quantity issues reviewed in Arnold Jr. and Gibbons, 1996; and quality issues reviewed in Makepeace et al., 1995). In addition to pavement and buildings, compacted soils are also sometimes categorized as impervious surface (Arnold Jr. and Gibbons, 1996; Gregory et al., 2006), and compacted soils adjacent to pavement may act as extensions of that impervious surface (Shuster et al., 2005), due to having low infiltration rates (Pitt et al., 2008). Thus, reducing compacted soil surface area in urban landscapes has potential to not only reduce impervious or near impervious surface overall, but may have an even greater effect on connected impervious surface. For example, compacted soil in a streetside planting area between a sidewalk and road may effectively connect two impervious areas, whereas if the soil were permeable, it would decrease runoff not only from the soil itself but from the adjacent sidewalk by disconnecting it from the street's storm sewer system.

In addition to reducing the stormwater infiltration and storage capacity of the soil, soil compaction also has a profound effect on the growth of vegetation, which also plays a role in stormwater mitigation. In particular, tree growth in urban areas is often challenging due to limited useable soil (Day and Amateis, 2011), with compacted soils limiting root growth (Materechera et al., 1991; Pan and Bassuk, 1985) and gas exchange (Stepniewski et al., 1994), thus, compaction reduces the volume of soil in which roots can grow. Urban tree canopy is known to reduce stormwater runoff due to interception and storage of rainfall (Xiao and McPherson, 2002). Trees and soils together are further able to reduce runoff by funneling precipitation below ground via interception, stemflow, and flow along root channels (Johnson and Lehmann, 2006). Because large trees in full leaf provide more ecosystem services than smaller trees or those with few leaves (Xiao and McPherson, 2002), urban soil health is of concern for the provision of stormwater management benefits and other services provided by trees. Thus, there is potential for soil management approaches that reduce compaction to reduce urban runoff both through direct interception and transmission of rainfall and indirectly through its effect on vegetation.

There is wide recognition among urban foresters and allied professions that urban soil conditions are often inadequate and may need to be improved before plantings can be installed. Two commonly used approaches for improving planting soil are soil replacement and soil amendment. Replacement typically involves excavating and removing existing soil and replacing it with a planting "topsoil" that may be imported from rural areas or manufactured from various combinations of screened mineral soils and organic amendments (Sloan et al., 2012). However, soil replacement may be expensive, importing natural replacement soils is not a sustainable practice, and manufactured blends may be droughty because they are designed to facilitate drainage (Sloan et al., 2012). Soil amendment, on the other hand, is limited to where existing soil has an acceptable pH, and is not composed of coarse construction waste or contaminated fill material. Because organic amendments such as composted yard waste or biosolids are relatively low-cost materials and make up only a small proportion of the resulting soil, amending urban soil is often more cost-effective than replacement.

There is some evidence that soil temperature may also be affected by soil amendment (Gupta et al., 1977), although this effect has not been studied on sites where deep (greater than 30 cm) incorporation of organic amendments has been used. Changes in soil temperature could have effects on both tree root growth periodicity (Graves, 1994; Harris et al., 1995; Kuhns et al., 1985) and possibly reduce heat transfer to runoff generated from landscapes. Higher temperature runoff from hot impervious surfaces results in elevated temperature in receiving streams which degrades fish habitat (Herb et al., 2008; LeBlanc et al., 1997; Van Buren et al., 2000), and can also lead to increased channel erosion (Parks, 2012).

Soil amendment via deep incorporation of compost may be an effective way to reduce urban soil compaction in the primary root zone of most urban trees (Chen et al., 2014; Layman et al., 2009; Layman, 2010), which is approximately in the top 1-2 m (Day et al., 2010b). Soil structure plays a significant role in soil permeability (Abu-Sharar et al., 1987; reviewed in Alaoui et al., 2011), and is closely linked to soil organic carbon (SOC) content, which can be increased by soil amendment (Chen et al., 2013), as soil aggregates are held together largely by organic compounds (Oades, 1993). Furthermore, inclusion of trees themselves aids in soil aggregate formation by releasing root exudates, compounds that cement soil particles (Bronick and Lal, 2005), as well as provides a carbon source for microbial activity in the vicinity (Tisdall et al., 1978). In this study we examine the effects of soil profile rebuilding, an amendment technique using deep incorporation of compost, in streetside plantings in a highly urbanized setting in Arlington, Virginia. Soil profile rebuilding was previously demonstrated to increase tree growth in controlled plot experiments on a simulated development site with a loam soil (Layman et al., 2009), subsoil hydraulic conductivity (Chen et al., 2014), and aggregate-protected carbon pools (Chen et al., 2013), and to also decrease bulk density at 15-20 cm depth (Chen et al., 2014). However, whether these effects will be evident in a highly urbanized setting has yet to be explored and effects on soil temperature are unknown. Our objectives were to determine the effects of soil profile rebuilding in new streetside tree plantings on:

1. Subsurface saturated hydraulic conductivity and surface near-saturated hydraulic conductivity
2. Soil organic carbon content and micro- and macro-aggregate-associated carbon pools.
3. Tree growth and establishment during the first year after site preparation and planting.

Methods

Study site

The study was conducted in Arlington, Virginia, USA where 25 plots, each consisting of an unpaved area (such as a median or tree lawn) designated for street tree planting, were located along two thoroughfares, South Walter Reed Drive near its intersection with South Four Mile Run Drive (38.847046, -77.094800) and North George Mason Drive beginning at the intersection of 15th Street and continuing to the intersection with Lee Highway (38.895427,-77.133510). Located in the Coastal Plain physiographic province of Virginia, Arlington has a temperate climate, with an average annual temperature of 13.17° C, and average annual rainfall 1085 mm.

Current soil surveys map study plots along both streets as urban land complex, however, the sites likely retain some characteristics of the pre-development soils (Effland and Pouyat, 1997). Adjacent soil series include Sassafras (Fine-loamy, siliceous, semiactive, mesic Typic Hapludults) and Neabsco (Fine-loamy, siliceous, semiactive, mesic Typic Fragiudults) soils at the plots along S Walter Reed Drive, and Glenelg (Fine-loamy, mixed, semiactive, mesic Typic Hapludults) at the plots along N George Mason Drive. The Sassafras series is well drained with moderate to high saturated hydraulic conductivity and loamy fluviomarine sediment parent material (NCSS, 2013). The Neabsco series is very deep and moderately well drained but with "very slow permeability". Neabsco soils have a fragipan between 17 and 36 inches deep (NCSS, 2013) and are "formed in stratified marine and fluvial sediments of the Coastal Plain" (NCSS, 1999). Glenelg soil series are very deep, well drained soils with moderately high saturated hydraulic conductivity in the subsoil. Glenelg soils were formed from weathered micaceous shist (NCSS, 2008). Soil textural class of soils at four depths are presented in table 4.1.

Table 4.1. Soil textural class range of soils at four depth intervals at each study location. Sampled from four cores per street.

	Walter Reed Drive	George Mason Drive
0-15cm	Sandy Loam – Loam	Sandy Loam
15-30cm	Sandy Loam – Loam	Sandy Loam – Clay Loam/Sandy Clay Loam
30-60cm	Sandy Loam – Loam	Sandy Loam – Sandy Clay Loam
60-90cm	Sandy Loam – Loam	Sandy Loam – Sandy Clay Loam

Treatments

Soil Profile Rebuilding (SPR) is a protocol for restoration of soil function to disturbed sites that includes compost amendment combined with a subsoiling technique. It is intended to reduce compaction in subsoil, and improve drainage and carbon storage over the long term. The method includes first removing and stockpiling any topsoil that may have been added to the site after disturbance. Once topsoil is removed, 10 cm of stable compost is spread across the area to be treated. Soil is then mixed to a depth of 60 cm by a scooping and dumping procedure using a backhoe. This step should take place when soil is neither very wet nor very dry. The soil-compost mixture is not homogenized, only broken up until no soil clods larger than 15 cm in diameter are present. After subsoiling, stockpiled topsoil is replaced or added to a depth of 10 cm and tilled to a depth of 15-20 cm. The final step is to plant the site with woody plants, preferably large maturing trees (Day et al., 2012).

The 25 plots in this study were created as a part of a city project to slow traffic. Treatments were randomly assigned to plots resulting in 13 control plots and 12 SPR plots, all of which were installed by Arlington County's landscape contractor. Fifteen of the plots were either parallel parking spaces or left-turn lanes, and were under pavement prior to their conversion to sidewalk "bump-out" tree pits or median plantings. The remaining 10 plots were not previously under pavement and were either on hillsides near intersections, in existing tree planting areas, or separated from the street by the sidewalk. All plots were within 5 m of the road. One plot was installed over buried transmission electric lines, thus only tree growth and temperature data were collected for this plot. Tree species and locations were selected by the Arlington Division of Transportation, with *G. biloba* being planted in the medians along N George Mason Drive, *Q. coccinea* in streetside plantings on N George Mason Drive, and *C. japonicum* in streetside plantings on S Walter Reed Drive.

We compared SPR with the standard site preparation methods used by Arlington County Parks and Recreation (control) where approximately 15 cm topsoil (sandy loam, pH of 5.5 to 6.5, minimum organic content of 1%, and free of debris >1.3 cm length) was placed over existing subsoil to bring the soil up to curb grade. The SPR plots also received topsoil to bring the soil up to the level of the curb. Both control and SPR plots were planted with one of three tree species: *Cercidiphylum japonicum* Siebold & Zucc., *Quercus coccinea* Muenchh. or *Ginkgo biloba* L.. Balled and burlapped trees approximately 60 mm diameter measured at 15.2 cm above the root ball were planted in October 2012 by digging a hole twice as wide as the root ball and nearly as deep as the height of the ball, exposing the highest root in the ball and backfilling with existing soil. Trees were not staked and 10 cm of shredded hardwood bark mulch was applied around the trees in a 1.2 m diameter ring. Soil Profile Rebuilding plots had new sod installed over the treatment, and existing turfgrass (that had been placed as sod earlier that year) was left in place after tree planting in control plots.

Field measurements

Infiltration

Infiltration as near-saturated hydraulic conductivity (K_{near}) of the soil matrix was measured using a mini disk tension infiltrometer (Decagon Devices, Inc., Pullman, WA) with -2 cm tension approximately 1 m from trees in each plot on May 15-16, 2014. Turf was trimmed at soil level and three measurements (treated as subsamples) were taken at each plot.

Soil temperature

Temperature sensors (Hobo® Tidbit v2, Onset, Bourne, MA) were installed 20 cm below the soil surface in each plot on June 24-26 2013, and logged temperature readings (±0.2°C) every 15 minutes until they were removed on June 21, 2014.

Tree growth

Tree growth was measured at the end of March 2013 and the end of February 2014. Trees were planted leaf-off during October 2012, thus the measurements taken represent size at planting and after one growing season. Measurement locations were marked with a paint pen to prevent varying the measurement location year to year. Diameter was measured to the nearest 0.1 mm at 15 cm, 30 cm and 130 cm from ground level, corresponding to caliper and diameter at breast height measurements common in the forestry and horticulture professions. Height was measured to the nearest 0.1 m with a Vertex III hypsometer (Haglöf, Långsele, Sweden). Crown width was measured in two dimensions using a plumb bob and a measuring tape, and height from ground to lowest branch was also measured in 2013.

Sample collection

Soils were sampled for total carbon, aggregate stability, bulk density and aggregate-associated carbon on November 1-3 and 25 2013. Soil cores were obtained with a JMC Environmentalist's Subsoil Probe (ESP; Clements Associates, Inc, Newton, IA). This instrument was driven into the soil manually with a slide hammer, and penetrated the soil to a depth of 92.8 cm. Cores were removed by jacking the sampling tube out of the ground resulting in a continuous core 2.9 cm in diameter. As an artifact of core extraction, the soil sample was slightly compressed during sample collection. The degree of compression was variable due to the relative compressibility of the soil. Therefore, the amount of sample compression was measured for every 15 cm that the sampler was advanced into the ground, the last interval being 17.8 cm. Soil with large rocks was problematic as rocks sometimes blocked the opening of the sampler, falsely indicating very high compression for a section of the sample. Samples were retaken in such cases. Compression of each 15 or 17.8 cm section was calculated and recorded as a percentage.

Cores were kept on ice during transport and then stored at 4°C at the Urban Horticulture Center on the Virginia Tech campus for later processing for analysis of particle size distribution, aggregate stability, total carbon and aggregate associated carbon.

Four soil cores (5 cm diameter X 5 cm tall) were taken from each plot with a slide hammer, one at each of the four sampling depths at approximately 5-10 cm, 20-25 cm, 42.5-47.5 cm, and 72.5-77.5 cm. Cores were used for analysis of bulk density and saturated hydraulic conductivity. Only 83 of the 96 planned samples were collected, primarily because of excessive stoniness. Samples from the two deepest depths could not be obtained due to high gravel or moisture content. Four samples from 30-60 cm depth and four samples from 60-90 cm were not collected from control plots, and three samples from 30-60 cm and two samples from 60-90 cm were not collected in SPR plots. Missing samples were not necessarily from the same plots (i.e. 60-90 cm sample was sometimes collected where 30-60 cm sample was not).

Soil analysis

Sample processing

Soil Profile Rebuilding treatment created two new layers in the soil profile (the top layer where topsoil was added and the interface with the subsoil was mixed approximately 15 cm deep, and the layer of compost incorporation from 15-60 cm) thus, four depths were identified for sampling: 0-15 cm, 15-30 cm, 30-60 cm and 60-90 cm. Compression percentages recorded in the field were used to separate the samples into 4 depth increments corresponding to 0-15, 15-30, 30-60 and 60-90 cm depths in the field. Because cores were compressed during sampling, it was necessary to calculate lengths of core segments that correspond to depths in the soil profile. Percent compaction as recorded at sampling was used in the lab to separate continuous cores into segments corresponding to 0-15, 15-30, 30-60 and 60-90 cm sections of the field soil.

Particle size distribution

Particle size distribution was analyzed from continuous cores from 8 plots considered representative of the range of soils included in the study. After being divided into the depths of interest (0-15 cm, 15-30 cm, 30-60 cm, and 60-90 cm) samples were hand mixed and subsamples were analyzed by the pipette method (Gee and Or, 2002). Gravels were sieved out of the sample after grinding and fine (2.0-12.7 mm) and coarse gravel content (>12.7 mm) was determined on a percent mass basis.

Hydraulic conductivity

Saturated hydraulic conductivity (K_{Sat}) of 5 cm X 5 cm cylindrical soil cores was measured in the lab with from January 13-24 2014 using the constant head method described in Klute and Dirksen (2003). Five of the 83 cores were not measured due to rocks extending beyond the end of the aluminum sleeve.

Bulk density

After cores were measured for K_{sat}, caps were removed and any adhering soil washed into a small aluminum pan with the core sample. Samples were oven dried for 24 hours at 105°C and weighed. Bulk density was calculated in both the "$\rho_{fine\text{-}earth}$" (density of the soil between rock fragments in the sample) and "ρ_{hybrid}" (density of the soil without the mass of rock fragments but with the entire sample volume) forms described by Throop et al. (2012), although rock volume was calculated from the mass of washed separated rocks (assumed particle density of 2.65 g/cm^3), instead of being measured by displacement. The "ρ_{hybrid}" bulk density was used for estimation of areal carbon densities, because the density of the soil when rocks are considered voids accurately accounts for the proportion of the soil-rock matrix that can contribute to soil carbon, and the "$\rho_{fine\text{-}earth}$" is used for discussion of changes in bulk density, as the density of the fine-earth fraction is most related to root growth restriction.

Aggregate size distribution

Aggregate size distribution was determined from samples extracted from each of the four layers in the deep continuous cores described above using the wet sieving methods described in Six et al. (1998). Fifty gram (±0.02 g) samples were placed on 2 mm sieves and slaked by being rapidly submerged in deionized water. Samples were allowed to equilibrate for 5 min, then the sieve was moved up and down for 50 strokes (counting both the up stroke and the down stroke) within a 2 min time period. Material remaining on the sieve was then washed into labeled aluminum pans. The water and material that had passed though the sieve was then poured onto a 250 µm sieve and sieved for 50 strokes. Material left on the sieve was washed into a labeled pan and the water and remaining material were poured onto a 53 µm sieve, and the process above repeated. Samples were dried at 55°C for 24 hours or until all water had evaporated from the pans. Sample weights were recorded and samples scraped from pans and stored in coin envelopes. Soil mean weight diameter was calculated according to Eq. (4.1):

145 $$MWD = (M_{>2000\mu m} \times 5) + (M_{250\text{-}2000\mu m} \times 1.125) + (M_{53\text{-}250\mu m} \times 0.151) + (M_{<53\mu m} \times 0.0265) \quad \text{[eq. 4.1]}$$

Aggregate fractions were corrected for rock and sand content according to Denef et al. (2001) Fractions were ground and dry-sieved to separate rocks, a subsample of the aggregates was placed in sodium hexametaphosphate solution and shaken overnight, and washed through a 53 µm sieve. Material remaining on the sieve was oven dried and weighed.

Carbon analysis

Total carbon analysis was performed using dry combustion on an Elementar Variomacro CN Analyzer (Elementar Analysensysteme GmbH, Hanau, Germany), all carbon was assumed to be organic. Soil core segments were broken apart by hand, mixed and air dried before a subsample was ground to be analyzed for total carbon. After sand corrections were done on aggregate fractions, the ground aggregate fraction samples were also analyzed using dry combustion on an Elementar Variomacro CN Analyzer (Elementar Analysensysteme GmbH Hanau, Germany) for aggregate-associated carbon.

Statistical analysis

Statistical analyses were conducted with Minitab 16 Statistical Software (Minitab, Inc., State College, PA) using two sample t-tests to analyze differences in soil characteristics between treatments. Normality assumptions were met, and the General Linear Model was used to check for interactions of treatment and species, due to the unbalanced design of the experiment.

Results and Discussion

Tree growth

Trees planted in SPR plots had a greater average increase in cross-sectional area measured at 15 cm above ground level after one growing season than trees in control plots [5.14 cm^2 (SE 0.62 cm^2) vs. 2.90 cm^2 (SE 0.37 cm^2) p=0.007]. This pattern was also observed within species, although there were too few experimental units with *G. biloba* to perform statistical tests (Fig. 4.1). We did not find evidence of significant differences in cross-sectional area growth at 30 cm and 1.30 m between SPR and control for any species or all trees together. This may be attributed to the small magnitude of increase (3.85 cm^2 (SE 0.53 cm^2) for SPR and 2.76 cm^2 (SE 0.38 cm^2) for control) at 30 cm and the high variability at 1.3 m due to many trees having branches below this height. No significant differences in the amount of height gain or crown volume increases were observed between trees in SPR and control plots. Growth increases were expected from SPR, but it was surprising that growth increases were evident after only one growing season, as this period after transplant is usually characterized by root regeneration and minimal shoot growth (Harris, 2007). However, greater trunk cross-sectional area growth was also seen at 30 cm above ground during the first year after installation in soil subjected to SPR for two of five tree species tested by Layman et al. (2009). Previous organic amendment studies with trees have focused primarily on amending planting holes as opposed to the entire site. Effects of planting hole amendment on tree growth is dependent on species, soil type, irrigation, type of nursery stock (Corley, 1984; Gilman, 2004), and amendment nitrogen content (Smalley and Wood, 1995). The relatively low C:N ratio (14.9:1) of compost in this study was likely able to provide N to trees unlike higher C amendments that can cause N stress when used as backfill (Smalley and Wood, 1995).

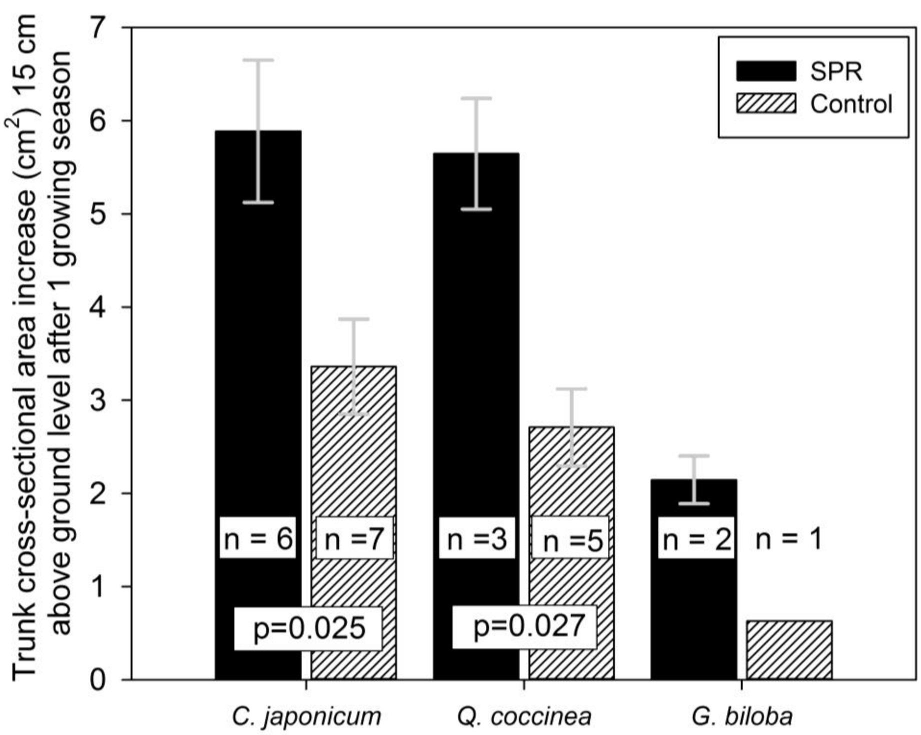

Figure 4.1. Mean increase in trunk cross sectional area at 15 cm above ground level for trees planted in Soil Profile Rebuilding and control plots after one growing season. Growth values for individual trees within plots with >1 tree were treated as subsamples, as treatment was assigned at the plot level.

Soil characteristics

During soil analysis, we did not find compost below a depth of approximately 35 cm in the soil samples, indicating that the contractor did not install the SPR treatment to the depth mandated in the specification. Had it been installed correctly, compost would have been seen at 60 cm depth (Day et al., 2012). Although the contractors were provided with a written specification, and the method was discussed in a telephone conference with the contractor, Arlington County project manager, urban forester and the authors, the contractor failed to follow the specification correctly. The method explored here is novel, and it seems that convincing the contractor that soil should be loosened to the unusually great depth of 60 cm was more difficult than expected. Because soil below 30-35 cm was essentially undisturbed due to improper installation, we focused our analyses at the 15 to 30 cm depth, instead of 15-60 cm, as originally planned.

Bulk density

Soil bulk density was significantly lower in SPR plots than in control plots at 15-30 cm depth but not at any other depth sampled (Table 4.2). Rivenshield and Bassuk (2007) saw >10% decreases in bulk density from the addition of organic matter at rates of 33% and 50% by volume for coarse and fine textured soils in a laboratory study, largely due to the lower particle density of organic matter compared to mineral soil. The compost additions in this study were not as great, but we still saw a small decrease in bulk density, likely due to dilution of mineral soil with organic material, as aggregate formation usually takes longer than the 13 months between installation and sampling (Wick et al., 2009b). Incorporation of compost into soil in the field also lowers bulk density, and the effect is increased by combining with surface applied organic mulch (Cogger et al., 2008). Chen et al. (2014) saw decreased bulk density at 15-20 cm depth due to

SPR treatment, yet found a higher bulk density at 50.8-55.9 cm depths in their SPR plots compared to untreated controls. This was unexpected because compost was incorporated at that depth, but may have been caused by the movement of the backhoe bucket during installation. Bulk density was also higher in SPR by 0.11 g/cm^3 at 30-60 cm depth in this study, although the difference was not significant (p=0.324).

Aggregate-associated carbon,aggregate size distribution, and total carbon

Soil Profile Rebuilding increased macro-aggregate-associated carbon at 15-30 cm depth for both the 250-2000 μm and the >2000 μm size classes (Table 4.2) (data significant at α=0.1). Sand-free macro-aggregate associated carbon was higher in SPR plots when the two macro-aggregate classes (250-2000 μm and >2000 μm) were combined [0.1131 g C /g sand-free aggregate (SE 0.022 g C /g) and 0.0451 g C /g sand-free aggregate (SE 0.011 g C /g) p=0.012], Changes in aggregate-associated carbon in micro-aggregates (<250 μm) were not significant between SPR and control (Table 4.2). Chen et al. (2014) saw higher macro-aggregate-associated carbon concentrations in SPR treated soil at 15-30 cm depth than in simulated development four years after the installation of SPR. We observed this same effect after only 13 months in this study. Mean weight diameter (MWD), an estimate of the average size of soil aggregates by weight (Van Bavel, 1950), was used to represent aggregate size distribution. We saw no differences in MWD among treatments after one year; similarly, Chen et al. (2014) found no differences after four and five years. Increases in macro-aggregate-associated carbon imply that carbon storage in the soil is increasing; however, we found no significant differences in total carbon between SPR and control soils, although means of SPR plots were higher in the three upper depths (data presented in Table 4.2). Because the subsoil is loosened and disturbed during installation, existing organic carbon is likely to be lost (Chen et al., 2014; Wick et al., 2009a), explaining the increase in the macro-aggregate associated carbon and lack of change in total organic carbon.

Table 4.2. Soil parameter means, with standard errors of the means in parenthesis measured at four depths in soil profile rebuilding (SPR) and control plots in Arlington, Virginia 13 months after treatment installation.

Depth (cm)	Bulk Density (g/cm^3)		Saturated Hydraulic Conductivity (cm/hr)		Total Carbon Density (kg C $/m^2$)		<250 μm Sand-Free Aggregate-Associated Carbon (g C /g sand-free aggregate)		2000-250 μm Sand-Free Aggregate-Associated Carbon (g C /g sand-free aggregate)		>2000 μm Sand-Free Aggregate-Associated Carbon (g C /g sand-free aggregate)		Mean Weight Diameter of Aggregates (mm)	
	SPR	Control	SPR	Control	SPR	Control	SPR	Control	SPR	Control	SPR	Control	SPR	Control
0-15	1.22 (0.08)	1.30 (0.07)	47.6 (19.5)	40.9 (17.0)	3.61 (0.49)	3.32 (0.42)	$2.43*10^{-2}$ ($3.7*10^{-3}$)	$3.18*10^{-2}$ ($7.7*10^{-3}$)	$1.1*10^{-1}$ ($2.4*10^{-2}$)	$7.24*10^{-2}$ ($1.3*10^{-2}$)	$4.08*10^{-2}$ ($4.9*10^{-3}$)	$4.35*10^{-2}$ ($4.7*10^{-3}$)	1.67 (0.13)	1.86 (0.19)
15-30	1.25 $(0.08)^+$	1.44 $(0.05)^+$	19.5 (8.1)	52.4 (31.3)	1.89 (0.33)	1.77 (0.35)	$1.84*10^{-2}$ ($2.6*10^{-3}$)	$1.61*10^{-2}$ ($5.1*10^{-3}$)	$1.17*10^{-1}$ $(3.0*10^{-2})^*$	$5.16*10^{-2}$ $(1.5*10^{-2})^*$	$1.05*10^{-1}$ $(3.3*10^{-2})^{§}$	$2.81*10^{-2}$ $(8.8*10^{-3})^{§}$	0.81 (0.13)	0.98 (0.16)
30-60	1.49 (0.06)	1.38 (0.09)	5.44 (4.0)	45.7 (23.1)	2.52 (0.35)	1.98 (0.32)	$1.16*10^{-2}$ ($1.7*10^{-3}$)	$1.16*10^{-2}$ ($2.4*10^{-3}$)	$5.24*10^{-2}$ ($1.1*10^{-2}$)	$3.68*10^{-2}$ ($9.7*10^{-3}$)	$5.34*10^{-2}$ ($2.7*10^{-2}$)	$8.5*10^{-3}$ ($2.4*10^{-3}$)	0.92 (0.06)	1.00 (0.14)
60-90	1.51 (0.07)	1.53 (0.03)	2.89 (1.7)	2.03 (1.0)	0.56 (0.17)	3.34 (2.6)	$4.28*10^{-3}$ ($1.4*10^{-3}$)	$1.06*10^{-2}$ ($5.9*10^{-3}$)	$1.50*10^{-2}$ ($9.3*10^{-3}$)	$2.40*10^{-2}$ ($1.1*10^{-2}$)	$2.13*10^{-2}$ ($1.3*10^{-2}$)	$1.04*10^{-2}$ (n=1)	1.10 (0.31)	0.72 (0.05)

$^+$ means significantly different (p=0.064)
* means significantly different (p=0.071)
§ means significantly different (p=0.087)

Saturated and near-saturated hydraulic conductivity

We did not see differences between SPR and control soil in near-saturated hydraulic conductivity (K_{near}) at the soil surface, with an overall mean K_{near} of 2.75 cm/hr (SE 0.39 cm/hr). There were also no differences between SPR and control in saturated hydraulic conductivity (K_{sat}) at any of the depths measured (Table 4.2). The lack of differences at the surface was expected, since surface treatments were virtually identical in SPR and control plots. Because measurements of K_{near} were made under tension and do not represent flow in large macropores (Beven and Germann, 2013), K_{near} and K_{sat} are not directly comparable. Although, as conductivity in subsoil layers tended to be higher by an order of magnitude (see Table 4.2), the surface layer may limit the amount of water that could flow through the profile. Chen et al.'s (2014) earlier study found K_{sat} was nearly 10 times higher than the simulated development at depths of 10-40 cm, the depth range most affected by SPR. Thus, we expected that differences in K_{sat} would occur at the 15-30 cm depth, where compost was incorporated. That no effect was detectable may be due to the core method we used to measure K_{sat}. Because K_{sat} is scale-dependent and SPR results in heterogeneous subsoil with soil clods interspersed with veins of compost, differences may have been evident if K_{sat} had been measured in situ, or on a larger scale, where larger cracks or water paths may have had more influence. The core method was chosen for this study because of the difficulty of conducting *in situ* measurements in dispersed urban plots. Cogger et al. (2008) saw increased infiltration at the surface from mulches as well as incorporated compost, compared to bare soil using the double-ring method. Because surface infiltration can be improved by compost addition, it may be of interest to see if incorporating compost into topsoil with SPR improves infiltration, as topsoil structure is degraded by the processes of removal, stockpiling and replacement (Chen et al., 2014).

Case study: Soil temperature

Overall, soil temperature patterns appeared to be buffered by SPR, although the plots used in this study were too variable in terms of sun exposure to provide overall statistical evidence to document this. Consequently, we compared temperature data from two plots that were well matched in terms of proximity, closeness to pavement, and solar exposure during the month of September (Fig. 4.2). Maximum and minimum temperatures recorded over the entire study period in the plots was 31.7°C and 31.4°C, and 0.3°C and 0.8°C for control and SPR plots respectively. Maximum temperatures occurred on July 19, 2013 at 6 PM and the minimum on January 31, 2014 for the SPR plot and on February 1 and 2, 2014 for the control. One sensor was disturbed by installation of an electrical box soon after it was placed, and was found within 1 cm of the surface. The maximum and minimum temperatures recorded by that sensor were 48.9°C (July 19) and -2.2°C (January 30) respectively.

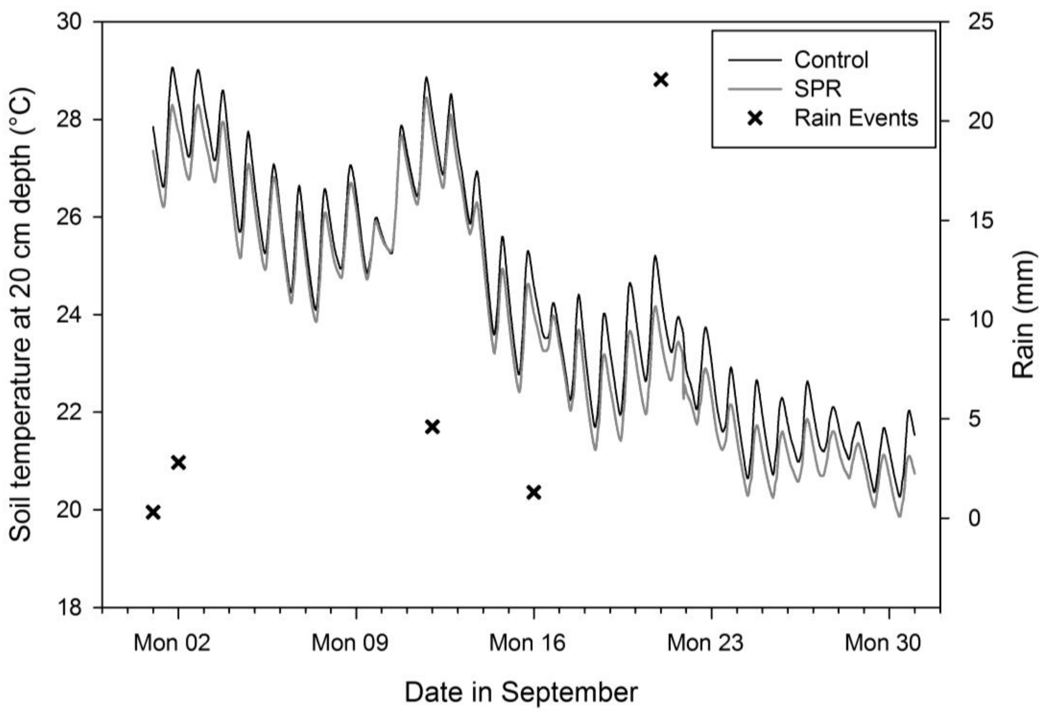

Figure 4.2. Soil temperature at 20 cm depth and rain events from September 1 to September 30, 2013 in one control and one SPR plot located less than 300 m apart, having similar aspect and distance to pavement.

As root growth is known to begin at soil temperatures around 4°C for some species (Kuhns et al., 1985), and 12 °C for others species including *Q. coccinea* (Harris et al., 1995), we tested whether there was a difference in the amount of time that plots spent above 12°C: the difference was approximately 45 minutes, and likely of no consequence. The control plot, however, did not drop below 12°C after April 10, 2013, while it was April 12, 2013 before the SPR plot had a full day with temperature above 12 °C. Root growth is known to stop in the fall when soil temperatures reach "-6 to 8°C" (Harris et al., 1995); soil temperature in the control plot dropped below 8°C one day before the SPR plot (November 24 vs 25), and was approximately 1°C cooler until the next warming event on December 2. Root growing season may have been shifted by the treatment, but does not seem to have been extended. Large rain events seem to cool the soil noticeably, although smaller events did not seem to have an effect. The buffering of soil temperature we observed in SPR plots may be due to decreased thermal conductivity of amended soil due to more air filled pores and increased water holding capacity, which could raise the amended soil's specific heat capacity (Gupta et al., 1977). Due to the opportunistic approach to soil temperature measurement in this study, there is a lack of statistical power with which to make blanket statements about SPR's influence on soil temperature. Root injury is known to occur around 32-35°C for *Gleditsia triacanthos* and *Acer rubrum* (Graves, 1994), near the maximums observed in this study. Buffering soil temperature with organic matter additions might reduce time spent at upper extremes, potentially preventing root injury. Little is known about soil temperatures in urban environments; Halverson and Heisler (1981) saw elevated (by 3°C) summer maximum soil temperature under parking lot trees compared to trees in undisturbed soil nearby, and also measured 10°C higher temperatures at 15 cm under asphalt, noting that temperatures fluctuated faster under asphalt than soil. Further study based on paired plots of similar solar input is needed. Rhizosphere temperatures under asphalt in Phoenix, AZ have been measured to 1 m depth and found to exceed 40°C in the summer (Celestian and Martin, 2004), enough to injure tree roots.

Conclusion

Soil profile rebuilding is a viable means to decrease soil bulk density at depth in urban areas. Our study corroborated results from a controlled study in finding that SPR decreased bulk density in the upper layers of subsoil as well as increased carbon associated with large aggregates. Trees planted into sites prepared with SPR are likely to establish faster than those planted without similar site preparation. The method may also be useful for increasing soil carbon storage in the long term on developed sites, as trees have increased growth during the first growing season after transplant, carbon inputs from roots are likely to be greater in SPR treated soil than in areas without such site preparation. Tree roots are expected to input carbon into deep regions in the soil profile, and total carbon may therefore increase on a slower timescale than macro-aggregate-associated carbon. Decreased soil bulk density implies higher porosity, which means more pore space is available to store water. However, our study did not find that SPR increased K_{sat} either at the surface or at the 15-30 cm depth where the soil was most altered. This is in contrast to findings in an earlier study, however, we measured K_{sat} in extracted soil cores which may not have adequately represented larger scale characteristics such as root paths, cracks, or clods, that can influence K_{sat} of the bulk soil. Urban stormwater could be managed with SPR, as this study saw faster establishment of transplanted trees growing and decreases in subsoil density, allowing for more water to be captured and stored than in typical urban soil. Faster tree establishment means faster returns on investment for municipalities using trees and soil for stormwater management, because large trees are more effective at capturing precipitation. Though SPR appeared to buffer soil temperatures to some extent, the actual temperature differences were slight and likely would have little influence on root growth, and temperature effects may have been masked by intermittent shade on the plots. Further research is needed to determine effects of SPR on soil temperature, and the subsequent effects on root growth, rhizotrons may be useful in such a study.

References

Abu-Sharar, T., Bingham, F., Rhoades, J., 1987. Reduction in hydraulic conductivity in relation to clay dispersion and disaggregation. Soil Science Society of America Journal 51, 342-346.

Alaoui, A., Lipiec, J., Gerke, H.H., 2011. A review of the changes in the soil pore system due to soil deformation: A hydrodynamic perspective. Soil and Tillage Research 115–116, 1-15.

Arnold Jr., C.L., Gibbons, C.J., 1996. Impervious surface coverage: The emergence of a key environmental indicator. Journal of the American Planning Association 62, 243-258.

Beven, K., Germann, P., 2013. Macropores and water flow in soils revisited. Water Resource Research 49, 3071-3092.

Booth, D.B., 1991. Urbanization and the natural drainage system--impacts, solutions, and prognoses. The Northwest Environmental Journal 7, 93-118.

Bronick, C.J., Lal, R., 2005. Soil structure and management: A review. Geoderma 124, 3-22.

Celestian, S.B., Martin, C.A., 2004. Rhizosphere, surface, and air temperature patterns at parking lots in Phoenix, Arizona, US. Journal of Arboriculture 30, 245-252.

Chen, Y., Day, S.D., Wick, A.F., McGuire, K.J., 2014. Influence of urban land development and subsequent soil rehabilitation on soil aggregates, carbon, and hydraulic conductivity. Science of the Total Environment.

Chen, Y., Day, S.D., Wick, A.F., Strahm, B.D., Wiseman, P.E., Daniels, W.L., 2013. Changes in soil carbon pools and microbial biomass from urban land development and subsequent post-development soil rehabilitation. Soil Biology and Biochemistry 66, 38-44.

Cogger, C., Hummel, R., Hart, J., Bary, A., 2008. Soil and redosier dogwood response to incorporated and surface-applied compost. HortScience 43, 2143-2150.

Corley, W., 1984. Soil amendments at planting. Journal of Environmental Horticulture 2, 27-30.

Day, S.D., Amateis, R.L., 2011. Predicting canopy and trunk cross-sectional area of silver linden (*Tilia tomentosa*) in confined planting cutouts. Urban Forestry and Urban Greening 10, 317-322.

Day, S.D., Layman, R.M., Chen, Y., Rolf, K., Daniels, W.L., Gugercin, S., Harris, J.R., Wiseman, P.E., McGuire, K.J., Strahm, B., Wick, A.F., Mauzy, B., 2012. Soil profile rebuilding, specification for restoration of graded and compacted soils that will be vegetated, p. 5.

Day, S.D., Wiseman, P., Dickinson, S.B., Harris, J.R., 2010. Contemporary concepts of root system architecture of urban trees. Arboriculture & Urban Forestry 36, 149.

Denef, K., Six, J., Bossuyt, H., Frey, S.D., Elliott, E.T., Merckx, R., Paustian, K., 2001. Influence of dry–wet cycles on the interrelationship between aggregate, particulate organic matter, and microbial community dynamics. Soil Biology and Biochemistry 33, 1599-1611.

Effland, W., Pouyat, R., 1997. The genesis, classification, and mapping of soils in urban areas. Urban Ecosystems 1, 217-228.

Gee, G.W., Or, D., 2002. 2.4 Particle-size analysis, in: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis: Part 4 Soil Science Society of America, Madison, WI, USA, pp. 255-293.

Gilman, E.F., 2004. Effects of amendments, soil additives, and irrigation on tree survival and growth. Journal of Arboriculture 30, 301-310.

Graves, W.R., 1994. Urban soil temperatures and their potential impact on tree growth. Journal of Arboriculture 20, 24-24.

Gregory, J.H., Dukes, M.D., Jones, P.H., Miller, G.L., 2006. Effect of urban soil compaction on infiltration rate. Journal of Soil and Water Conservation 61, 117-124.

Gupta, S.C., Dowdy, R.H., Larson, W.E., 1977. Hydraulic and thermal properties of a sandy soil as influenced by incorporation of sewage sludge. Soil Science Society of America Journal 41, 601-605.

Halverson, H.G., Heisler, G.M., 1981. Soil temperatures under urban trees and asphalt. USDA Forest Service Research Paper.

Harris, J., 2007. Transplanting large trees. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition, and Natural Resources 2, 024.

Harris, J.R., Bassuk, N.L., Zobel, R.W., Whitlow, T.H., 1995. Root and shoot growth periodicity of green ash, scarlet oak, Turkish hazelnut, and tree lilac. Journal of the American Society for Horticultural Science 120, 211-216.

Herb, W.R., Janke, B., Mohseni, O., Stefan, H.G., 2008. Thermal pollution of streams by runoff from paved surfaces. Hydrological Processes 22, 987-999.

Johnson, M.S., Lehmann, J., 2006. Double-funneling of trees: Stemflow and root-induced preferential flow. Ecoscience 13, 324-333.

Klein, R.D., 1979. Urbanization and stream quality impairment. Journal of the American Water Resources Association 15, 948-963.

Klute, A., Dirksen, C., 2003. Hydraulic conductivity and diffusivity: Laboratory methods, in: Klute, A. (Ed.), Methods of Soil Analysis: Part 1 Soil Science Society of America, pp. 687-734.

Kuhns, M., Garrett, H., Teskey, R., Hinckley, T., 1985. Root growth of black walnut trees related to soil temperature, soil water potential, and leaf water potential. Forest Science 31, 617-629.

Layman, R., Day, S., Harris, J., Daniels, W., Wiseman, P., 2009. Rehabilitation of severely compacted urban soil to optimize tree establishment and growth, II International Conference on Landscape and Urban Horticulture 881, pp. 505-509.

Layman, R.M., 2010. The effect of soil rehabilitation of severely compacted urban soils to optimize tree establishment and growth, Horticulture. Virginia Tech, p. 114.

LeBlanc, R.T., Brown, R.D., FitzGibbon, J.E., 1997. Modeling the effects of land use change on the water temperature in unregulated urban streams. Journal of Environmental Management 49, 445-469.

Makepeace, D.K., Smith, D.W., Stanley, S.J., 1995. Urban stormwater quality: summary of contaminant data. Critical Reviews in Environmental Science and Technology 25, 93-139.

Materechera, S., Dexter, A., Alston, A., 1991. Penetration of very strong soils by seedling roots of different plant species. Plant and Soil 135, 31-41.

Moscrip, A.L., Montgomery, D.R., 1997. Urbanization, flood frequency, and salmon abundance in Puget lowland streams. Journal of the American Water Resources Association 33, 1289-1297.

NCSS, 1999. Neabsco Series. National Cooperative Soil Survey.

NCSS, 2008. Glenelg Series. National Cooperative Soil Survey.

NCSS, 2013. Sassafras Series. National Cooperative Soil Survey.

Oades, J.M., 1993. The role of biology in the formation, stabilization and degradation of soil structure. Geoderma 56, 377-400.

Pan, E., Bassuk, N., 1985. Effects of soil type and compaction on the growth of Ailanthus altissima seedlings. Journal of Environmental Horticulture 2, 158-162.

Parks, O.W., 2012. Effect of water temperature on cohesive soil erosion, Biological Systems Engineering. Virginia Tech, Blacksburg, VA, p. 61.

Pitt, R., Chen, S.-E., Clark, S.E., Swenson, J., Ong, C.K., 2008. Compaction's impacts on urban storm-water infiltration. Journal of Irrigation and Drainage Engineering 134, 652-658.

Rivenshield, A., Bassuk, N.L., 2007. Using organic amendments to decrease bulk density and increase macroporosity in compacted soils. Arboriculture and Urban Forestry 33, 140.

Seto, K.C., Güneralp, B., Hutyra, L.R., 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proceedings of the National Academy of Sciences 109, 16083-16088.

Shuster, W., Bonta, J., Thurston, H., Warnemuende, E., Smith, D., 2005. Impacts of impervious surface on watershed hydrology: A review. Urban Water Journal 2, 263-275.

Six, J., Elliott, E., Paustian, K., Doran, J., 1998. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. Soil Science Society of America Journal 62, 1367-1377.

Sloan, J.J., Ampim, P.A., Basta, N.T., Scott, R., 2012. Addressing the need for soil blends and amendments for the highly modified urban landscape. Soil Science Society of America Journal 76, 1133-1141.

Smalley, T.J., Wood, C., 1995. Effect of backfill amendment on growth of red maple. Journal of Arboriculture 21, 247-247.

Stepniewski, W., Ball, B., Soane, B., Ouwerkerk, C.v., 1994. Effects of compaction on soil aeration properties, in: Soane, B.D., Ouwerkerk, C.v. (Eds.), Soil compaction in crop production. Elsevier Science Publishers, Amsterdam, Netherlands, pp. 167-189.

Throop, H., Archer, S., Monger, H.C., Waltman, S., 2012. When bulk density methods matter: Implications for estimating soil organic carbon pools in rocky soils. Journal of Arid Environments 77, 66-71.

Tisdall, J., Cockroft, B., Uren, N., 1978. The stability of soil aggregates as affected by organic materials, microbial activity and physical disruption. Soil Research 16, 9-17.

United Nations, 2012. World Urbanization Prospects, the 2011 Revision. United Nations, Department of Economic and Social Affairs, Population Division.

Van Bavel, C., 1950. Mean weight-diameter of soil aggregates as a statistical index of aggregation. Soil Science Society of America Journal 14, 20-23.

Van Buren, M.A., Watt, W.E., Marsalek, J., Anderson, B.C., 2000. Thermal enhancement of stormwater runoff by paved surfaces. Water Research 34, 1359-1371.

Wick, A., Stahl, P., Ingram, L., Vicklund, L., 2009a. Soil aggregation and organic carbon in short-term stockpiles. Soil Use and Management 25, 311-319.

Wick, A.F., Ingram, L.J., Stahl, P.D., 2009b. Aggregate and organic matter dynamics in reclaimed soils as indicated by stable carbon isotopes. Soil Biology and Biochemistry 41, 201-209.

Xiao, Q., McPherson, E.G., 2002. Rainfall interception by Santa Monica's municipal urban forest. Urban Ecosystems 6, 291-302.

Chapter 5: Conclusions

Urban land area is expanding across the globe, and environmental problems associated with urban land will likely expand as well. Impervious surfaces are nearly ubiquitous in urban land, and their presence nearly always causes drastic changes to local hydrology as compared to the pre-development condition. Engineered stormwater management infrastructure including storm sewers and treatment plants have been the traditional solution to the problem of increased surface water in cities, but stormwater best management practices (BMPs) have become popular over the last 20 years. These BMPs often use vegetation and infiltration to manage stormwater, and low impact development (LID) techniques have been created to attempt to manage stormwater on a parcel scale through infiltration-based BMPs. Such installations, however, are typically in a small area of the landscape surrounding new structures, and a logical extension of LID is that the entire landscape in new developments could be managed for some level of stormwater mitigation. Investigating the hydrologic behavior common ornamental mulches, and examining a site preparation method for improving permeability and tree establishment is a logical starting point for creating a dispersed stormwater management strategy.

Stormwater remains an issue, and while the service of interception and storage of precipitation by urban forests is widely understood, land development practices often leave landscapes with highly compact soils that become saturated quickly and cannot facilitate growth of trees to their genetic potential. By restoring urban soils to functionality, trees can grow larger and intercept more precipitation, and urban soils can accept more water from directly from precipitation and stemflow from trees. In turn, incoming water will be partitioned to surface flow, groundwater levels will increase, and stream baseflow and water quality will likely improve as well. In addition to resulting cool temperatures from baseflow improving water quality, more shade on impervious surfaces can decrease surface flow temperatures.

Ornamental mulches are typically used primarily for their aesthetic qualities, with decreasing weed competition and maintaining soil moisture as peripheral benefits. In agricultural and construction settings, mulches may also be used for erosion control and prevention of soil crusting, but typically non-ornamental mulch types are employed for those purposes. Our investigation of ornamental mulches for stormwater control indicates that choice of ornamental mulch type and placement can have significant effects on how an urban landscape performs in terms of mitigating the effects of urban runoff. We found, for example, that mulches can influence the speed and suspended solids concentration of runoff from soil surfaces. Geotextiles, frequently used beneath inorganic and also some organic mulches, may be useful for extending the life of running surfaces on gravel trails, but their use as a separator between mulch and soil in trafficked areas will lead to more runoff than if the fabric were omitted. Wood chips, in contrast, are quite resilient in their ability to slow runoff before and after traffic, and could be employed on paths for pedestrians to prevent unsightly death of turf at sidewalk intersections. While mulches as running surfaces may not prevent compaction, they do slow stormwater runoff, decrease sediment loss, and if organic mulches are used, can improve soil quality over time. The omission of plants from the mulch study allowed the behavior of soil moisture that was only lost to percolation and evaporation to be seen. In areas where rainfall is frequent and thus soil moisture is not often depleted, mulches may cause more runoff than bare soil due to the lack of evaporation loss between events. However, most of the eastern USA experiences strong storms that are infrequent, and most landscapes have tree roots depleting water from beneath mulched surfaces. Thus soil moisture would likely be reduced enough that increased runoff from mulched areas is unlikely.

Leveling large areas of land and removing topsoil is common practice in modern development, the results are often a dense soil with few pores and depleted organic carbon that is inhospitable for tree growth. Deep amendment with compost has been shown to address the tree growth and soil density issues within one year after installation. Continued growth resulting in large trees is likely to increase soil carbon over time, and simply amending the soil with compost increased the amount of carbon associated with large aggregates.

By lowering soil density and making the soil more amenable for tree growth, stormwater management can occur in a dispersed manner, using tree canopy to intercept precipitation that would otherwise fall on streets, roofs, or sidewalks. Combining intelligent choices and placement of mulch materials may also help grow large trees, and is able to slow runoff that does occur on soils. While we were unable to detect a compaction-preventing quality in any mulches tested, it is possible that under lighter traffic, mulch may prevent increases in bulk density. Through combining smart mulch placement and long-term soil improvement techniques, municipalities could save measurable dollars on stormwater treatment, and potentially increase carbon storage in urban soils. Such savings could be passed on to residents and businesses, by creating a local tax break that reflects the savings created by keeping stormwater on site, and managing soils and landscapes for environmental benefit. This would not only save people money, but encourage development of landscapes that would provide additional benefits such as energy savings, air pollution reductions, and improvements of psychological health. Further research is needed to assess effects of deep compost amendment on soil temperature and its influences on carbon cycling and root growth periodicity. Testing of mulches under actual foot traffic for their ability to prevent compaction could provide valuable knowledge for preserving mature trees in recreational space. Combining widespread mulching, turf cover and SPR for comparison of infiltration capacity and moisture storage would help inform decisions about groundcover choices in dispersed stormwater management. If people are deterred by from using parks with large mulched areas, other, health related ecosystem services would be sacrificed for stormwater control, thus, preferences of surface cover for resting/picnicking should also be investigated to inform placement strategy of stormwater-slowing groundcover.

Bibliography

Abu-Sharar, T., Bingham, F., Rhoades, J., 1987. Reduction in hydraulic conductivity in relation to clay dispersion and disaggregation. Soil Science Society of America Journal 51, 342-346.

Adams, C.E., Lindsey, K.J., 2012. Anthropogenic Ecosystems: The Influence of People on Urban Wildlife Populations, in: Niemalä, J. (Ed.), Urban Ecology: Patterns, Processes, and Applications. Oxford University Press, Oxford, NY, pp. 116-128.

Adams, J.E., 1966. Influence of mulches on runoff, erosion, and soil moisture depletion. Soil Science Society of America Journal 30, 110-114.

Adekalu, K.O., Okunade, D.A., Osunbitan, J.A., 2006. Compaction and mulching effects on soil loss and runoff from two southwestern Nigeria agricultural soils. Geoderma 137, 226-230.

Akbari, H., Kurn, D.M., Bretz, S.E., Hanford, J.W., 1997. Peak power and cooling energy savings of shade trees. Energy and Buildings 25, 139-148.

Akbari, H., Pomerantz, M., Taha, H., 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Solar Energy 70, 295-310.

Alakukku, L., 1996. Persistence of soil compaction due to high axle load traffic. I. Short-term effects on the properties of clay and organic soils. Soil and Tillage Research 37, 211-222.

Alakukku, L., Weisskopf, P., Chamen, W.C.T., Tijink, F.G.J., van der Linden, J.P., Pires, S., Sommer, C., Spoor, G., 2003. Prevention strategies for field traffic-induced subsoil compaction: a review: Part 1. Machine/soil interactions. Soil and Tillage Research 73, 145-160.

Alaoui, A., Lipiec, J., Gerke, H.H., 2011. A review of the changes in the soil pore system due to soil deformation: A hydrodynamic perspective. Soil and Tillage Research 115–116, 1-15.

Alberty, C., Pellett, H., Taylor, D., 1984. Characterization of soil compaction at construction sites and woody plant response. Journal of Environmental Horticulture 2, 48-53.

American Public Health Association, 1995. Solids, in: Eaton, A.D., Clesceri, L.S., Greenberg, A.E. (Eds.), Standard Methods for the Examination of Water and Wastewater, 19th ed. APHA, Washington, DC, p. 53.

Arnold Jr., C.L., Gibbons, C.J., 1996. Impervious surface coverage: The emergence of a key environmental indicator. Journal of the American Planning Association 62, 243-258.

Asaeda, T., Ca, V.T., Wake, A., 1996. Heat storage of pavement and its effect on the lower atmosphere. Atmospheric Environment 30, 413-427.

Atucha, A., Merwin, I.A., Brown, M.G., 2011. Long-term effects of four groundcover management systems in an apple orchard. HortScience 46, 1176-1183.

Bartens, J., Day, S.D., Harris, J.R., Dove, J.E., Wynn, T.M., 2008. Can urban tree roots improve infiltration through compacted subsoils for stormwater management? Journal of Environmental Quality 37, 2048-2057.

Bartens, J., Day, S.D., Harris, J.R., Wynn, T.M., Dove, J.E., 2009. Transpiration and root development of urban trees in structural soil stormwater reservoirs. Environmental Management 44, 646-657.

Bartens, J., Wiseman, P.E., Smiley, E.T., 2010. Stability of landscape trees in engineered and conventional urban soil mixes. Urban Forestry & Urban Greening 9, 333-338.

Batjes, N.H., 1996. Total carbon and nitrogen in the soils of the world. European Journal of Soil Science 47, 151-163.

Beesley, L., 2012. Carbon storage and fluxes in existing and newly created urban soils. Journal of Environmental Management 104, 158-165.

Beeson, R., Keller, K.G., 2001. Yard waste compost as a landscape soil amendment for azaleas. Journal of Environmental Horticulture 19, 222-225.

Berthier, E., Andrieu, H., Creutin, J.D., 2004. The role of soil in the generation of urban runoff: development and evaluation of a 2D model. Journal of Hydrology 299, 252-266.

Beven, K., Germann, P., 1982. Macropores and water flow in soils. Water Resources Research 18, 1311-1325.

Beven, K., Germann, P., 2013. Macropores and water flow in soils revisited. Water Resources Research 49, 3071-3092.

Billeaud, L.A., Zajicek, J.M., 1989. Influence of mulches on weed control, soil pH, soil nitrogen content, and growth of *Ligustrum japonicum*. Journal of Environmental Horticulture 7, 155-157.

Bilotta, G.S., Brazier, R.E., 2008. Understanding the influence of suspended solids on water quality and aquatic biota. Water Research 42, 2849-2861.

Black, K.E., Harbron, C.G., Franklin, M., Atkinson, D., Hooker, J.E., 1998. Differences in root longevity of some tree species. Tree Physiology 18, 259-264.

Booltink, H.W.G., Hatano, R., Bouma, J., 1993. Measurement and simulation of bypass flow in a structured clay soil: a physico-morphological approach. Journal of Hydrology 148, 149-168.

Booth, D.B., 1991. Urbanization and the natural drainage system--impacts, solutions, and prognoses. The Northwest Environmental Journal 7, 93-118.

Bramley, H., Hutson, J., Tyerman, S.D., 2003. Floodwater infiltration through root channels on a sodic clay floodplain and the influence on a local tree species Eucalyptus largiflorens. Plant and Soil 253, 275-286.

Brevik, E., Fenton, T., Moran, L., 2002. Effect of soil compaction on organic carbon amounts and distribution, South-Central Iowa. Environmental Pollution 116, S137-S141.

Bronick, C.J., Lal, R., 2005. Soil structure and management: A review. Geoderma 124, 3-22.

Buchanan, J., 2002. Wood chips as a soil cover for construction sites with steep slopes. Applied Engineering in Agriculture 18, 679-684.

Burgess, S.S., Adams, M.A., Turner, N.C., White, D.A., Ong, C.K., 2001. Tree roots: Conduits for deep recharge of soil water. Oecologia 126, 158-165.

Celestian, S.B., Martin, C.A., 2004. Rhizosphere, surface, and air temperature patterns at parking lots in Phoenix, Arizona, US. Journal of Arboriculture 30, 245-252.

Chalker-Scott, L., 2007. Impact of mulches on landscape plants and the environment-A review. Journal of Environmental Horticulture 25, 239.

Chen, Y., Day, S.D., Wick, A.F., McGuire, K.J., 2014. Influence of urban land development and subsequent soil rehabilitation on soil aggregates, carbon, and hydraulic conductivity. Science of The Total Environment.

Chen, Y., Day, S.D., Wick, A.F., Strahm, B.D., Wiseman, P.E., Daniels, W.L., 2013. Changes in soil carbon pools and microbial biomass from urban land development and subsequent post-development soil rehabilitation. Soil Biology and Biochemistry 66, 38-44.

Cogger, C., Hummel, R., Hart, J., Bary, A., 2008. Soil and redosier dogwood response to incorporated and surface-applied compost. Hortscience 43, 2143-2150.

Cole, D.N., Fichtler, R.K., 1983. Campsite impact on three western wilderness areas. Environmental Management 7, 275-288.

Corley, W., 1984. Soil amendments at planting. Journal of Environmental Horticulture 2, 27-30.

Costanza, R., d'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'neill, R.V., Paruelo, J., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253-260.

Craul, P.J., 1994. Soil compaction on heavily used sites. Journal of Arboriculture 20, 69-69.

Craul, P.J., Klein, C.J., 1980. Characterization of streetside soils of Syracuse, New York, Metropolitan Tree Improvement Alliance (METRIA) Proceedings, pp. 88-101.

Davis, A.P., Hunt, W.F., Traver, R.G., Clar, M., 2009. Bioretention technology: Overview of current practice and future needs. Journal of Environmental Engineering 135, 109-117.

Day, S., Seiler, J., Persaud, N., 2000. A comparison of root growth dynamics of silver maple and flowering dogwood in compacted soil at differing soil water contents. Tree Physiology 20, 257-263.

Day, S.D., Amateis, R.L., 2011. Predicting canopy and trunk cross-sectional area of silver linden (*Tilia tomentosa*) in confined planting cutouts. Urban Forestry and Urban Greening 10, 317-322.

Day, S.D., Bassuk, N.L., 1994. Effects of soil compaction and amelioration treatments on landscape trees. Journal of Arboriculture 20, 9-9.

Day, S.D., Eric Wiseman, P., Dickinson, S.B., Roger Harris, J., 2010a. Tree root ecology in the urban environment and implications for a sustainable rhizosphere. Journal of Arboriculture 36, 193.

Day, S.D., Layman, R.M., Chen, Y., Rolf, K., Daniels, W.L., Gugercin, S., Harris, J.R., Wiseman, P.E., McGuire, K.J., Strahm, B., Wick, A.F., Mauzy, B., 2012. Soil Profile Rebuilding, Specification for Restoration of Graded and Compacted Soils that will be Vegetated, p. 5.

Day, S.D., Wiseman, P., Dickinson, S.B., Harris, J.R., 2010b. Contemporary concepts of root system architecture of urban trees. Arboriculture & Urban Forestry 36, 149.

Denef, K., Six, J., Bossuyt, H., Frey, S.D., Elliott, E.T., Merckx, R., Paustian, K., 2001. Influence of dry–wet cycles on the interrelationship between aggregate, particulate organic matter, and microbial community dynamics. Soil Biology and Biochemistry 33, 1599-1611.

Deurer, M., Mueller, K., Kim, I., Huh, K., Young, I., Jun, G., Clothier, B., 2012. Can minor compaction increase soil carbon sequestration? A case study in a soil under a wheel-track in an orchard. Geoderma 183, 74-79.

Devitt, D.A., Smith, S.D., 2002. Root channel macropores enhance downward movement of water in a Mojave Desert ecosystem. Journal of Arid Environments 50, 99-108.

Dexter, A., 1988. Advances in characterization of soil structure. Soil and Tillage Research 11, 199-238.

Dietz, M., 2007. Low impact development practices: A review of current research and recommendations for future directions. Water, Air, and Soil Pollution 186, 351-363.

Dietz, M.E., Clausen, J.C., 2005. A field evaluation of rain garden flow and pollutant treatment. Water, Air, and Soil Pollution 167, 123-138.

Dietz, M.E., Clausen, J.C., 2006. Saturation to improve pollutant retention in a rain garden. Environmental Science & Technology 40, 1335-1340.

Donnelly, J.R., Shane, J.B., 1986. Forest ecosystem responses to artificially induced soil compaction. I. Soil physical properties and tree diameter growth. Canadian Journal of Forest Research 16, 750-754.

Effland, W., Pouyat, R., 1997. The genesis, classification, and mapping of soils in urban areas. Urban Ecosystems 1, 217-228.

Endreny, T.A., 2005. Land use and land cover effects on runoff processes: Urban and suburban development. Encyclopedia of hydrological sciences.

Entry, J.A., Reeves, D.W., Mudd, E., Lee, W.J., Guertal, E., Raper, R.L., 1996. Influence of compaction from wheel traffic and tillage on arbuscular mycorrhizae infection and nutrient uptake by Zea mays. Plant and Soil 180, 139-146.

Escobedo, F.J., Kroeger, T., Wagner, J.E., 2011. Urban forests and pollution mitigation: Analyzing ecosystem services and disservices. Environmental Pollution 159, 2078-2087.

Eswaran, H., Van Den Berg, E., Reich, P., 1993. Organic Carbon in Soils of the World. Soil Science Society of America Journal 57, 192-194.

Faucette, L., Jordan, C., Risse, L., Cabrera, M., Coleman, D., West, L., 2005. Evaluation of stormwater from compost and conventional erosion control practices in construction activities. Journal of Soil and Water Conservation 60, 288-297.

Fite, K., Smiley, E.T., McIntyre, J., Wells, C.E., 2011. Evaluation of a soil decompaction and amendment process for urban trees. Arboriculture & Urban Forestry 37, 293-300.

Freeman, E., Loehr, J.E., Bowders, J.J., 2000. Geotextile separators for hike and bike trail. Geotechnical Special Publication, 377-387.

Fulcher, G.A., 1994. Urban stormwater quality from a residential catchment. Science of The Total Environment 146–147, 535-542.

Garcia-Fresca, B., Sharp Jr, J.M., 2005. Hydrogeologic considerations of urban development: Urban-induced recharge. Reviews in Engineering Geology 16, 123-136.

Gee, G.W., Or, D., 2002. 2.4 Particle-size analysis, in: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis: Part 4 Soil Science Society of America, Madison, WI, USA, pp. 255-293.

George, K., Ziska, L.H., Bunce, J.A., Quebedeaux, B., 2007. Elevated atmospheric CO2 concentration and temperature across an urban–rural transect. Atmospheric Environment 41, 7654-7665.

Gilman, E.F., 2004. Effects of amendments, soil additives, and irrigation on tree survival and growth. Journal of Arboriculture 30, 301-310.

Gilman, E.F., Grabosky, J., 2004. Mulch and planting depth affect live oak (Quercus virginiana Mill.) establishment. Journal of Arboriculture 30, 311-317.

Godbold, D.L., Hoosbeek, M.R., Lukac, M., Cotrufo, M.F., Janssens, I.A., Ceulemans, R., Polle, A., Velthorst, E.J., Scarascia-Mugnozza, G., De Angelis, P., 2006. Mycorrhizal hyphal turnover as a dominant process for carbon input into soil organic matter. Plant and Soil 281, 15-24.

Grabosky, J., Bassuk, N., 1995. A new urban tree soil to safely increase rooting volumes under sidewalks. Journal of Arboriculture 21, 187-187.

Graves, W.R., 1994. Urban soil temperatures and their potential impact on tree growth. Journal of Arboriculture 20, 24-24.

Gregory, J.H., Dukes, M.D., Jones, P.H., Miller, G.L., 2006. Effect of urban soil compaction on infiltration rate. Journal of Soil and Water Conservation 61, 117-124.

Guo, J.C.Y., 2008. Volume-based imperviousness for storm water designs. Journal of Irrigation and Drainage Engineering-Asce 134, 193-196.

Gupta, S.C., Dowdy, R.H., Larson, W.E., 1977. Hydraulic and thermal properties of a sandy soil as influenced by incorporation of sewage sludge. Soil Science Society of America Journal 41, 601-605.

Halverson, H.G., Heisler, G.M., 1981. Soil temperatures under urban trees and asphalt. USDA Forest Service Research Paper.

Harris, J., 2007. Transplanting large trees. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition, and Natural Resources 2, 024.

Harris, J.R., Bassuk, N.L., Zobel, R.W., Whitlow, T.H., 1995. Root and shoot growth periodicity of green ash, scarlet oak, Turkish hazelnut, and tree lilac. Journal of the American Society for Horticultural Science 120, 211-216.

Heath, J., Ayres, E., Possell, M., Bardgett, R.D., et al., 2005. Rising atmospheric CO2 reduces sequestration of root-derived soil carbon. Science 309, 1711-1713.

Heathwaite, L., Haygarth, P., Matthews, R., Preedy, N., Butler, P., 2005. Evaluating colloidal phosphorus delivery to surface waters from diffuse agricultural sources. Journal of Environmental Quality 34, 287-298.

Herb, W.R., Janke, B., Mohseni, O., Stefan, H.G., 2008. Thermal pollution of streams by runoff from paved surfaces. Hydrological Processes 22, 987-999.

Hong, E., Seagren, E.A., Davis, A.P., 2006. Sustainable oil and grease removal from synthetic stormwater runoff using bench-scale bioretention studies. Water Environment Research 78, 141-155.

Hsieh, C.-H., Davis, A.P., 2005. Multiple-event study of bioretention for treatment of urban storm water runoff. Water Science & Technology 51, 177-181.

Idso, C.D., Idso, S.B., Balling Jr, R.C., 1998. The urban CO2 dome of Phoenix, Arizona. Physical Geography 19, 95-108.

Iles, J.K., Dosmann, M.S., 1999. Effect of organic and mineral mulches on soil properties and growth of Fairview Flame red maple trees. Journal of Arboriculture 25, 163-167.

Institute, S., SAS Version 9.3. SAS Institute Inc., Cary, NC, USA.

Jackson, N., Wallace, J., 1999. Analysis of soil water dynamics in an agroforestry system based on detailed soil water records from time-domain reflectometry. Hydrology and Earth System Sciences Discussions 3, 517-527.

Jackson, N., Wallace, J., Ong, C., 2000. Tree pruning as a means of controlling water use in an agroforestry system in Kenya. Forest Ecology and Management 126, 133-148.

Jastrow, J.D., 1996. Soil aggregate formation and the accrual of particulate and mineral-associated organic matter. Soil Biology and Biochemistry 28, 665-676.

Jim, C., 1993. Soil compaction as a constraint to tree growth in tropical & subtropical urban habitats. Environmental Conservation 20, 35-49.

Jim, C., 1998. Urban soil characteristics and limitations for landscape planting in Hong Kong. Landscape and Urban Planning 40, 235-249.

Johnson, M.S., Lehmann, J., 2006. Double-funneling of trees: Stemflow and root-induced preferential flow. Ecoscience 13, 324-333.

Jones, M.P., Hunt, W.F., 2009. Bioretention impact on runoff temperature in trout sensitive waters. Journal of Environmental Engineering 135, 577-585.

Jones, M.P., Hunt, W.F., 2010. Effect of storm-water wetlands and wet ponds on runoff temperature in trout sensitive waters. Journal of Irrigation and Drainage Engineering 136, 656-661.

Jones, M.P., Hunt, W.F., Winston, R.J., 2012. Effect of urban catchment composition on runoff temperature. Journal of Environmental Engineering 138, 1231-1236.

Jordán, A., Zavala, L.M., Gil, J., 2010. Effects of mulching on soil physical properties and runoff under semi-arid conditions in southern Spain. Catena 81, 77-85.

Jurskis, V., 2005. Eucalypt decline in Australia, and a general concept of tree decline and dieback. Forest Ecology and Management 215, 1-20.

Klein, R.D., 1979. Urbanization and stream quality impairment. Journal of the American Water Resources Association 15, 948-963.

Klute, A., Dirksen, C., 2003. Hydraulic conductivity and diffusivity: Laboratory methods, in: Klute, A. (Ed.), Methods of Soil Analysis: Part 1 Soil Science Society of America, pp. 687-734.

Koenker, K.M., 2002. User preference for trail surface material, Department of Landscape Architecture. University of Manitoba, Winnipeg, Canada.

Komatsu, H., Katayama, A., Hirose, S., Kume, A., Higashi, N., Ogawa, S., Otsuki, K., 2007. Reduction in soil water availability and tree transpiration in a forest with pedestrian trampling. Agricultural and Forest Meteorology 146, 107-114.

Kozlowski, T., 1999. Soil compaction and growth of woody plants. Scandinavian Journal of Forest Research 14, 596-619.

Kuhns, M., Garrett, H., Teskey, R., Hinckley, T., 1985. Root growth of black walnut trees related to soil temperature, soil water potential, and leaf water potential. Forest Science 31, 617-629.

Layman, R., Day, S., Harris, J., Daniels, W., Wiseman, P., 2009. Rehabilitation of severely compacted urban soil to optimize tree establishment and growth, II International Conference on Landscape and Urban Horticulture 881, pp. 505-509.

Layman, R.M., 2010. The effect of soil rehabilitation of severely compacted urban soils to optimize tree establishment and growth, Horticulture. Virginia Tech, p. 114.

LeBlanc, R.T., Brown, R.D., FitzGibbon, J.E., 1997. Modeling the effects of land use change on the water temperature in unregulated urban streams. Journal of Environmental Management 49, 445-469.

Lerner, D.N., 2002. Identifying and quantifying urban recharge: a review. Hydrogeology Journal 10, 143-152.

Lichter, J.M., Lindsey, P.A., 1994. The use of surface treatments for the prevention of soil compaction during site construction. Journal of Arboriculture 20, 205-205.

Lukac, M., Calfapietra, C., Godbold, D.L., 2003. Production, turnover and mycorrhizal colonization of root systems of three Populus species grown under elevated CO2 (POPFACE). Global Change Biology 9, 838-848.

Makepeace, D.K., Smith, D.W., Stanley, S.J., 1995. Urban stormwater quality: summary of contaminant data. Critical Reviews in Environmental Science and Technology 25, 93-139.

Matamala, R., Gonzalez-Meler, M.A., Jastrow, J.D., Norby, R.J., Schlesinger, W.H., 2003. Impacts of fine root turnover on forest NPP and soil C sequestration potential. Science 302, 1385-1387.

Materechera, S., Dexter, A., Alston, A., 1991. Penetration of very strong soils by seedling roots of different plant species. Plant and Soil 135, 31-41.

McPherson, E.G., Simpson, J.R., Xiao, Q., Wu, C., 2011. Million trees Los Angeles canopy cover and benefit assessment. Landscape and Urban Planning 99, 40-50.

Mitchell, A., Ellsworth, T., Meek, B., 1995. Effect of root systems on preferential flow in swelling soil. Communications in Soil Science & Plant Analysis 26, 2655-2666.

Morin, J., Benyamini, Y., 1977. Rainfall infiltration into bare soils. Water Resources Research 13, 813-817.

Moscrip, A.L., Montgomery, D.R., 1997. Urbanization, flood frequency, and salmon abundance in Puget lowland streams. Journal of the American Water Resources Association 33, 1289-1297.

NCSS, 1999. Neabsco Series. https://soilseries.sc.egov.usda.gov/OSD_Docs/N/NEABSCO.html. December 12, 2013.

NCSS, 2008. Glenelg Series. https://soilseries.sc.egov.usda.gov/OSD_Docs/G/GLENELG.html. December 12, 2013.

NCSS, 2013. Sassafras Series. https://soilseries.sc.egov.usda.gov/OSD_Docs/S/SASSAFRAS.html. December 12, 2013.

Neller, R., 1988. A comparison of channel erosion in small urban and rural catchments, Armidale, New South Wales. Earth Surface Processes and Landforms 13, 1-7.

Oades, J.M., 1993. The role of biology in the formation, stabilization and degradation of soil structure. Geoderma 56, 377-400.

Oliveira, M., Merwin, I., 2001. Soil physical conditions in a New York orchard after eight years under different groundcover management systems. Plant and Soil 234, 233-237.

Pan, E., Bassuk, N., 1985. Effects of soil type and compaction on the growth of Ailanthus altissima seedlings. Journal of Environmental Horticulture 2, 158-162.

Park, S.-J., Cheng, Z., Yang, H., Morris, E.E., Sutherland, M., Gardener, B.B.M., Grewal, P.S., 2010. Differences in soil chemical properties with distance to roads and age of development in urban areas. Urban Ecosystems 13, 483-497.

Parks, O.W., 2012. Effect of water temperature on cohesive soil erosion, Biological Systems Engineering. Virginia Tech, Blacksburg, VA, p. 61.

Patterson, J.C., 1977. Soil compaction--effects on urban vegetation. Journal of Arboriculture 3.

Pepper, P., E.; , McPherson, G., Simpson, J., Gardner, S., Vargas, K., Xiao, Q., 2007. New York City, New York Municipal forest resource analysis. Web.

Pitt, R., Chen, S.-E., Clark, S.E., Swenson, J., Ong, C.K., 2008. Compaction's impacts on urban storm-water infiltration. Journal of Irrigation and Drainage Engineering 134, 652-658.

Poland, T.M., McCullough, D.G., 2006. Emerald ash borer: Invasion of the urban forest and the threat to North America's Ash resource. Journal of Forestry 104, 118-124.

Pouyat, R.V., Yesilonis, I.D., Nowak, D.J., 2006. Carbon storage by urban soils in the United States. Journal of Environmental Quality 35, 1566-1575.

Price, K., Jackson, C.R., Parker, A.J., 2010. Variation of surficial soil hydraulic properties across land uses in the southern Blue Ridge Mountains, North Carolina, USA. Journal of Hydrology 383, 256-268.

Randrup, T.B., Dralle, K., 1997. Influence of planning and design on soil compaction in construction sites. Landscape and Urban Planning 38, 87-92.

Ray, A.B., Selvakumar, A., Tafuri, A.N., 2006. Removal of selected pollutants from aqueous media by hardwood mulch. Journal of Hazardous Materials 136, 213-218.

Rees, W.E., 1997. Urban ecosystems: The human dimension. Urban Ecosystems 1, 63-75.

Rivenshield, A., Bassuk, N.L., 2007. Using organic amendments to decrease bulk density and increase macroporosity in compacted soils. Arboriculture and Urban Forestry 33, 140.

Roy, S., Byrne, J., Pickering, C., 2012. A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones. Urban Forestry & Urban Greening 11, 351-363.

Rutter, A., Kershaw, K., Robins, P., Morton, A., 1972. A predictive model of rainfall interception in forests, 1. Derivation of the model from observations in a plantation of Corsican pine. Agricultural Meteorology 9, 367-384.

Sahin, V., Hall, M.J., 1996. The effects of afforestation and deforestation on water yields. Journal of Hydrology 178, 293-309.

Scharenbroch, B.C., 2009. A meta-analysis of studies published in Arboriculture & Urban Forestry relating to organic materials and impacts on soil, tree, and environmental properties. Arboriculture & Urban Forestry 35, 221-231.

Scharenbroch, B.C., Lloyd, J.E., Johnson-Maynard, J.L., 2005. Distinguishing urban soils with physical, chemical, and biological properties. Pedobiologia 49, 283-296.

Seto, K.C., Güneralp, B., Hutyra, L.R., 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proceedings of the National Academy of Sciences 109, 16083-16088.

Shuster, W., Bonta, J., Thurston, H., Warnemuende, E., Smith, D., 2005. Impacts of impervious surface on watershed hydrology: A review. Urban Water Journal 2, 263-275.

Six, J., Elliott, E., Paustian, K., Doran, J., 1998. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. Soil Science Society of America Journal 62, 1367-1377.

Sjöman, J.D., Gill, S.E., 2013. Residential runoff – The role of spatial density and surface cover, with a case study in the Höjeå river catchment, southern Sweden. Urban Forestry & Urban Greening.

Skroch, W., Powell, M., Bilderback, T., Henry, P., 1992. Mulches: Durability, aesthetic value, weed control, and temperature. Journal of Environmental Horticulture 10, 43-45.

Sloan, J.J., Ampim, P.A., Basta, N.T., Scott, R., 2012. Addressing the need for soil blends and amendments for the highly modified urban landscape. Soil Science Society of America Journal 76, 1133-1141.

Smalley, T.J., Wood, C., 1995. Effect of backfill amendment on growth of red maple. Journal of Arboriculture 21, 247-247.

Smiley, E.T., Calfee, L., Fraedrich, B.R., Smiley, E.J., 2006. Comparison of structural and noncompacted soils for trees surrounded by pavement. Arboriculture and Urban Forestry 32, 164.

Smith, E.P., 2006. BACI Design, Encyclopedia of environmetrics. John Wiley & Sons, Ltd.

Solecki, W.D., Rosenzweig, C., Parshall, L., Pope, G., Clark, M., Cox, J., Wiencke, M., 2005. Mitigation of the heat island effect in urban New Jersey. Global Environmental Change Part B: Environmental Hazards 6, 39-49.

Stephens, D.B., Miller, M., Moore, S.J., Umstot, T., Salvato, D.J., 2012. Decentralized groundwater recharge systems using roofwater and stormwater runoff. Journal of the American Water Resources Association.

Stepniewski, W., Ball, B., Soane, B., Ouwerkerk, C.v., 1994. Effects of compaction on soil aeration properties, in: Soane, B.D., Ouwerkerk, C.v. (Eds.), Soil compaction in crop production. Elsevier Science Publishers, Amsterdam, Netherlands, pp. 167-189.

Throop, H., Archer, S., Monger, H.C., Waltman, S., 2012. When bulk density methods matter: Implications for estimating soil organic carbon pools in rocky soils. Journal of Arid Environments 77, 66-71.

Tiessen, H., Cuevas, E., Chacon, P., 1994. The role of soil organic matter in sustaining soil fertility. Nature 371, 783-785.

Tisdall, J., Cockroft, B., Uren, N., 1978. The stability of soil aggregates as affected by organic materials, microbial activity and physical disruption. Soil Research 16, 9-17.

Tisdall, J., Oades, J.M., 1982. Organic matter and water-stable aggregates in soils. Journal of Soil Science 33, 141-163.

Townsend-Small, A., Pataki, D.E., Liu, H., Li, Z., Wu, Q., Thomas, B., 2013. Increasing summer river discharge in southern California, USA, linked to urbanization. Geophysical Research Letters 40, 4643-4647.

United Nations, Department of Economic and Social Affairs, Population Division, 2012. World Urbanization Prospects, the 2011 Revision. http://esa.un.org/unup/. Apr 10, 2013.

USEPA, Trees and Vegetation | Heat Island Effect | US EPA. http://www.epa.gov/heatisland/mitigation/trees.htm. June 14, 2014.

USEPA, 2004. National water quality inventory: Report to Congress. Environmental Protection Agency.

Van Bavel, C., 1950. Mean weight-diameter of soil aggregates as a statistical index of aggregation. Soil Science Society of America Journal 14, 20-23.

Van Buren, M.A., Watt, W.E., Marsalek, J., Anderson, B.C., 2000. Thermal enhancement of stormwater runoff by paved surfaces. Water Research 34, 1359-1371.

Wang, J., Endreny, T.A., Nowak, D.J., 2008. Mechanistic simulation of tree effects in an urban water balance model. Journal of the American Water Resources Association 44, 75-85.

Ware, G., 1990. Constraints to tree growth imposed by urban soil alkalinity. Journal of Arboriculture 16, 35-38.

Watson, G., Kelsey, P., Woodtli, K., 1996. Replacing soil in the root zone of mature trees for better growth. Journal of Arboriculture 22, 167-173.

Watson, G.W., 2002. Soil replacement: Long-term results. Journal of Arboriculture 28, 229-230.

Wick, A., Stahl, P., Ingram, L., Vicklund, L., 2009a. Soil aggregation and organic carbon in short-term stockpiles. Soil Use and Management 25, 311-319.

Wick, A.F., Ingram, L.J., Stahl, P.D., 2009b. Aggregate and organic matter dynamics in reclaimed soils as indicated by stable carbon isotopes. Soil Biology and Biochemistry 41, 201-209.

Winston, R., Hunt, W., Lord, W., 2011. Thermal mitigation of urban storm water by level spreader–vegetative filter strips. Journal of Environmental Engineering 137, 707-716.

Woltemade, C.J., 2010. Impact of residential soil disturbance on infiltration rate and stormwater runoff. Journal of the American Water Resources Association 46, 700-711.

Xiao, Q., McPherson, E.G., 2002. Rainfall interception by Santa Monica's municipal urban forest. Urban Ecosystems 6, 291-302.

Xiao, Q., McPherson, E.G., 2011. Performance of engineered soil and trees in a parking lot bioswale. Urban Water Journal 8, 241-253.

Yunusa, I., Mele, P., Rab, M., Schefe, C., Beverly, C., 2002. Priming of soil structural and hydrological properties by native woody species, annual crops, and a permanent pasture. Soil Research 40, 207-219.

Zhang, B.A., Xie, G.D., Zhang, C.Q., Zhang, J., 2012. The economic benefits of rainwater-runoff reduction by urban green spaces: A case study in Beijing, China. Journal of Environmental Management 100, 65-71.

Zhang, Z., Rengel, Z., Liaghati, T., Antoniette, T., Meney, K., 2011. Influence of plant species and submerged zone with carbon addition on nutrient removal in stormwater biofilter. Ecological Engineering 37, 1833-1841.

Zinger, Y., Blecken, G.-T., Fletcher, T.D., Viklander, M., Deletić, A., 2013. Optimising nitrogen removal in existing stormwater biofilters: Benefits and tradeoffs of a retrofitted saturated zone. Ecological Engineering 51, 75-82.

Zisa, R.P., Halverson, H.G., Stout, B.B., 1980. Establishment and early growth of conifers on compact soils in urban areas. USDA Forest Service Research Paper.

Ziska, L.H., Bunce, J.A., Goins, E.W., 2004. Characterization of an urban-rural CO2/temperature gradient and associated changes in initial plant productivity during secondary succession. Oecologia 139, 454-458.

Appendix . Annotated List of Figures

Figure 3.4. Plastic sheeting was used to isolate experimental units during rainfall simulation and shield adjacent plots from overspray. The sheeting also piped excess water out of the work area.

Figure 3.5. Runoff collection pan and bottle.

Figure 6.3. The compaction treatment was performed by running a jumping-jack style compactor over a 38 mm thick plywood disk on each plot. The disk was slightly smaller than the plot to avoid disturbing plot borders.

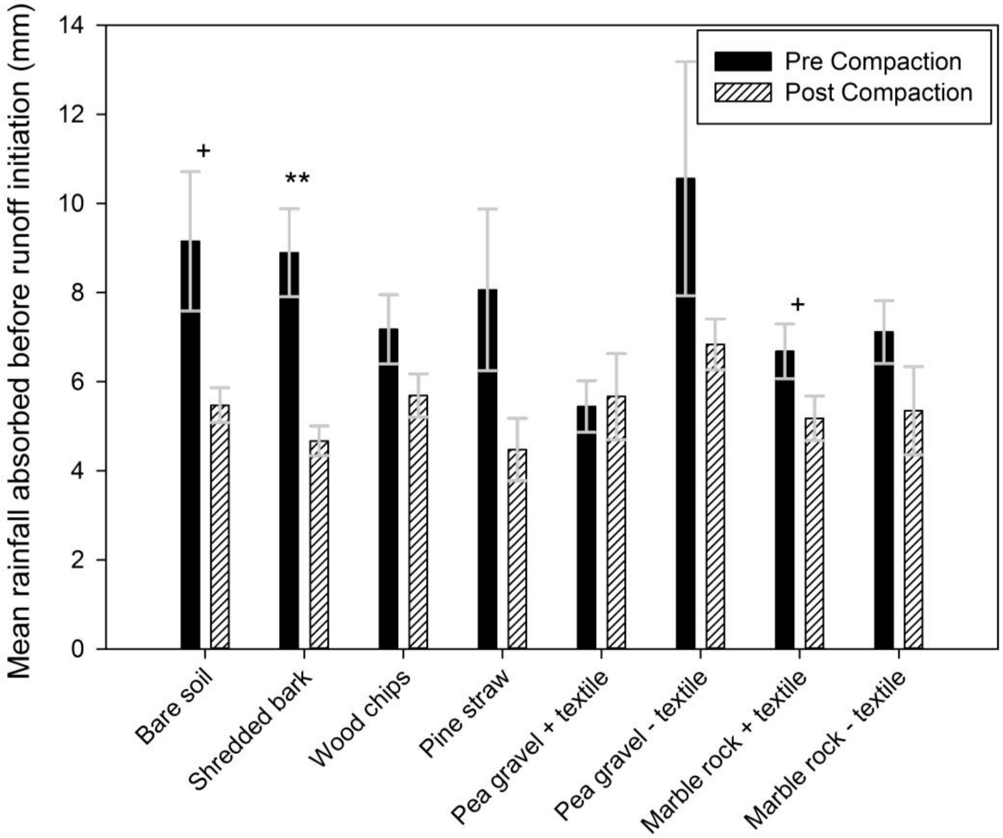

Figure 3.4. Mean rainfall absorbed by soil and surface cover before runoff initiated. Data are shown for rainfall simulations before and after compaction treatment. Differences before and after compaction significant at $p<0.1$, $p<0.05$, and $p<0.01$ indicated by +, *, and ** respectively. Mean rain rate 132 mm/h (standard error of mean = 1.89). Error bars represent standard errors of the means (n=6).

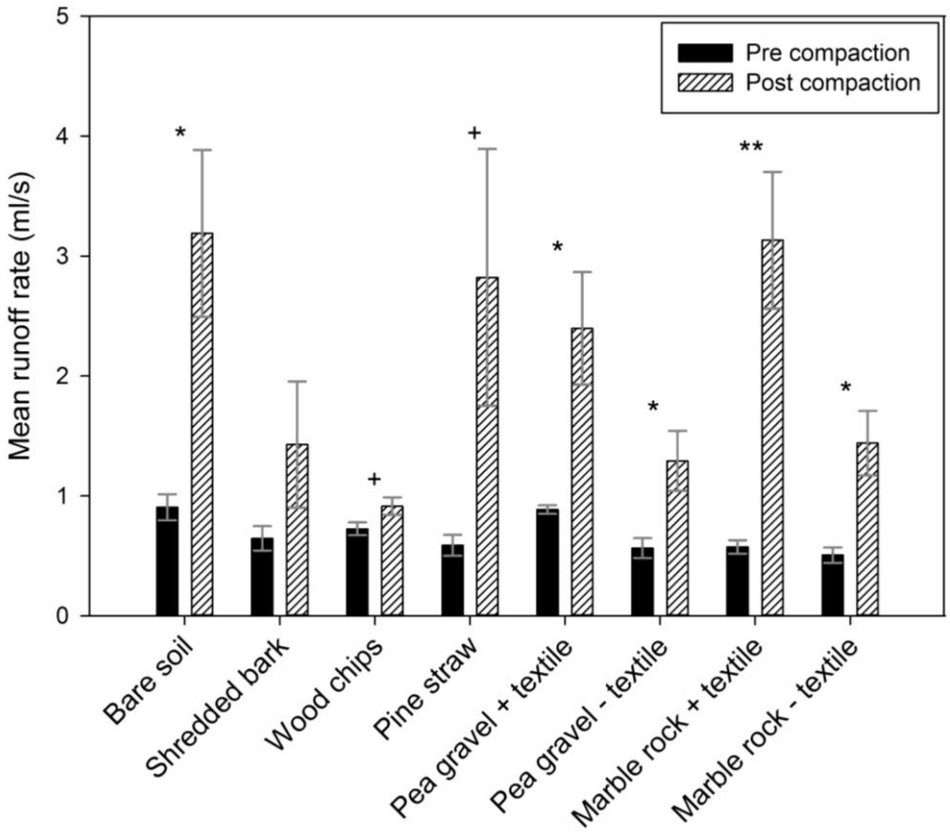

Figure 3.5. Mean runoff rates from plots before and after compaction treatment. Differences of before and after compaction significant at p<0.1, p<0.05, and p<0.01 indicated by +, *, and ** respectively. Mean rain rate of 132 mm/h (standard error of mean = 1.89). Bars represent standard errors of the means (n=6).

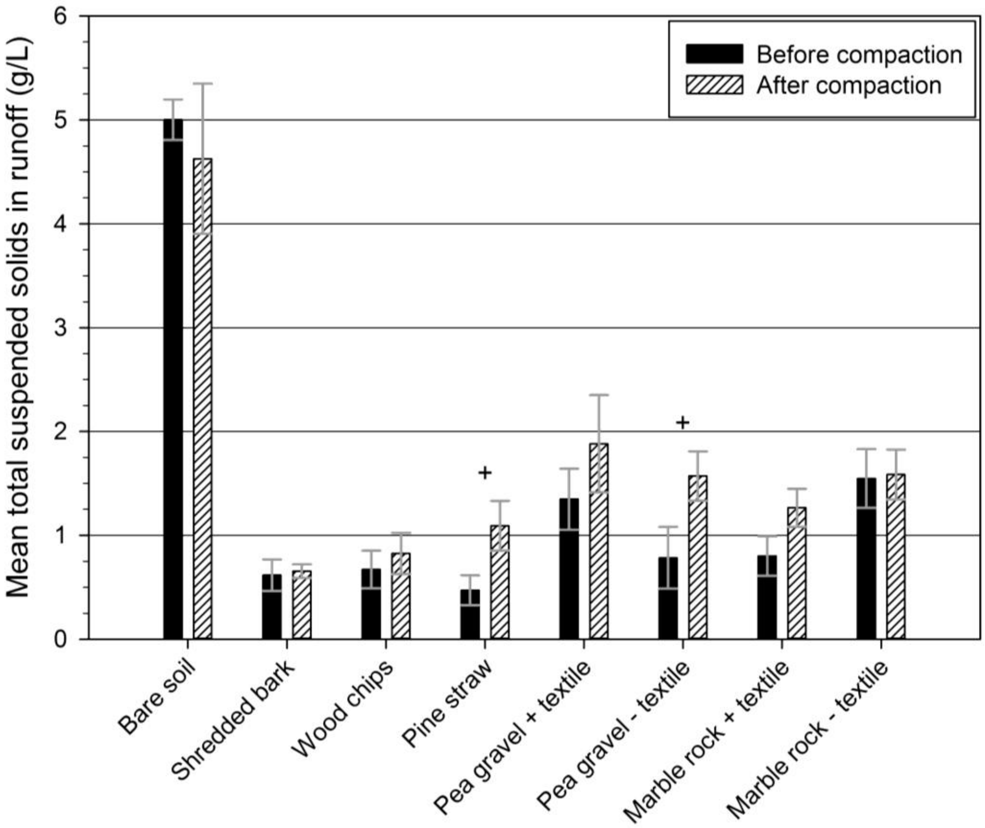

Figure 3.6. Mean total suspended solids (TSS) concentration of runoff collected under simulated rainfall from plots with 8 different surface cover types before and after compaction. Differences of before and after compaction means significant at $p<0.1$, $p<0.05$, and $p<0.01$ are indicated by +, *, and ** respectively. Mean rain rate of 132 mm/h (standard error of mean = 1.89). Bars represent standard errors of the means (n=6). For statistics see Table 3.2.

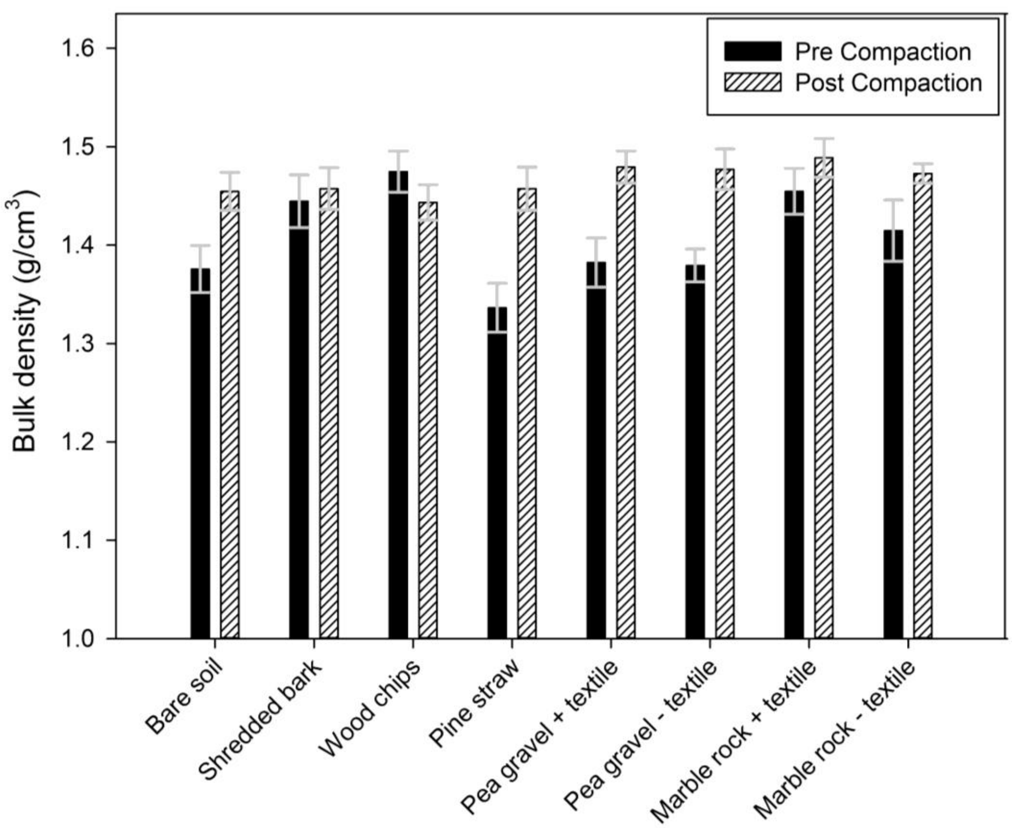

Figure 3.7. Mean soil bulk density at 5-10 cm depth before and after compaction treatment. Bars represent standard errors of the means (n=6).

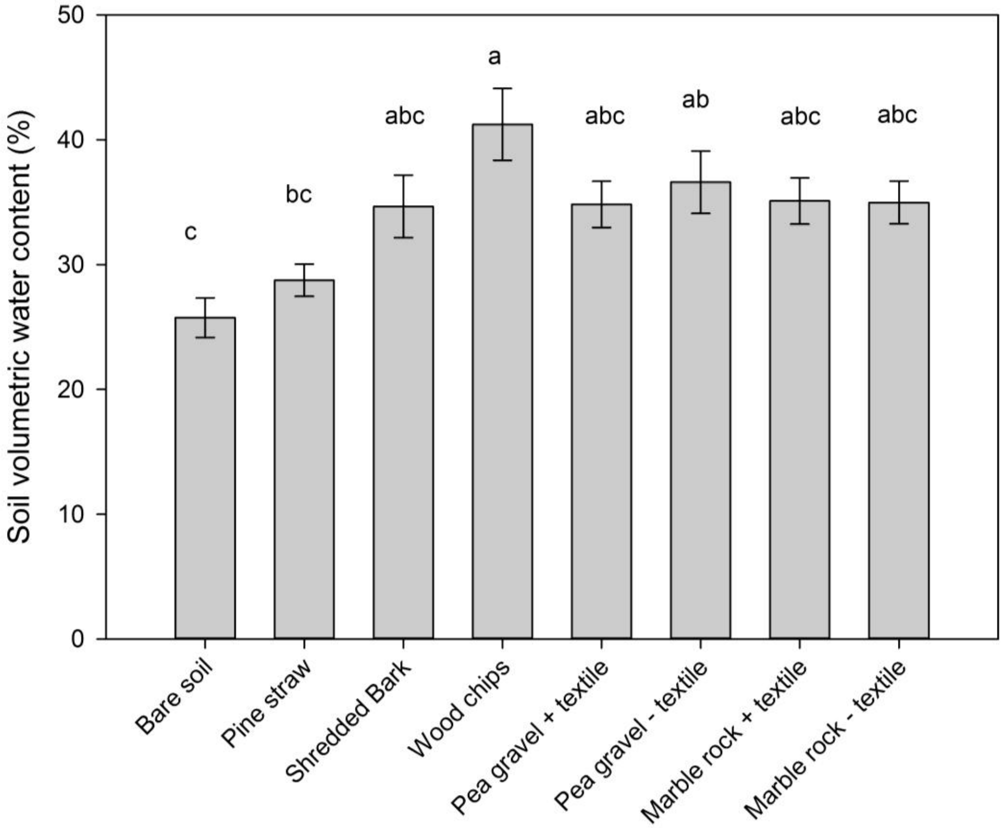

Figure 3.8. Mean soil volumetric water content 0-10 cm under different surface treatments 2 days after 2 rain events totaling 22.8 mm. Columns that do not share a letter are significantly different at α=0.05 using Tukey's HSD. Bars represent standard errors of the means (n=6).

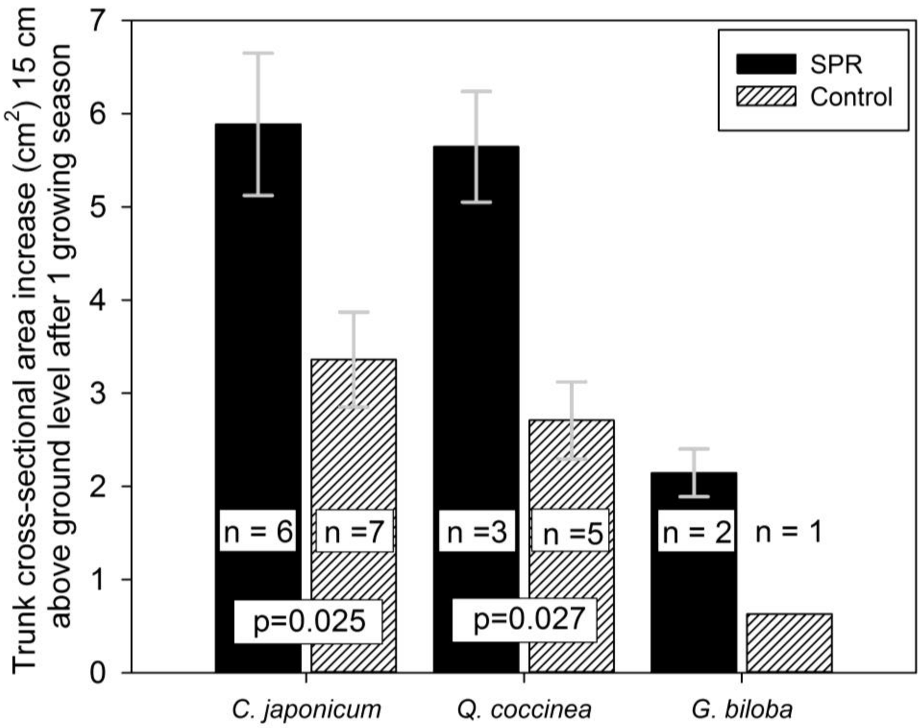

Figure 4.1. Mean increase in trunk cross sectional area at 15 cm above ground level for trees planted in Soil Profile Rebuilding and control plots after one growing season. Growth values for individual trees within plots with >1 tree were treated as subsamples, as treatment was assigned at the plot level.

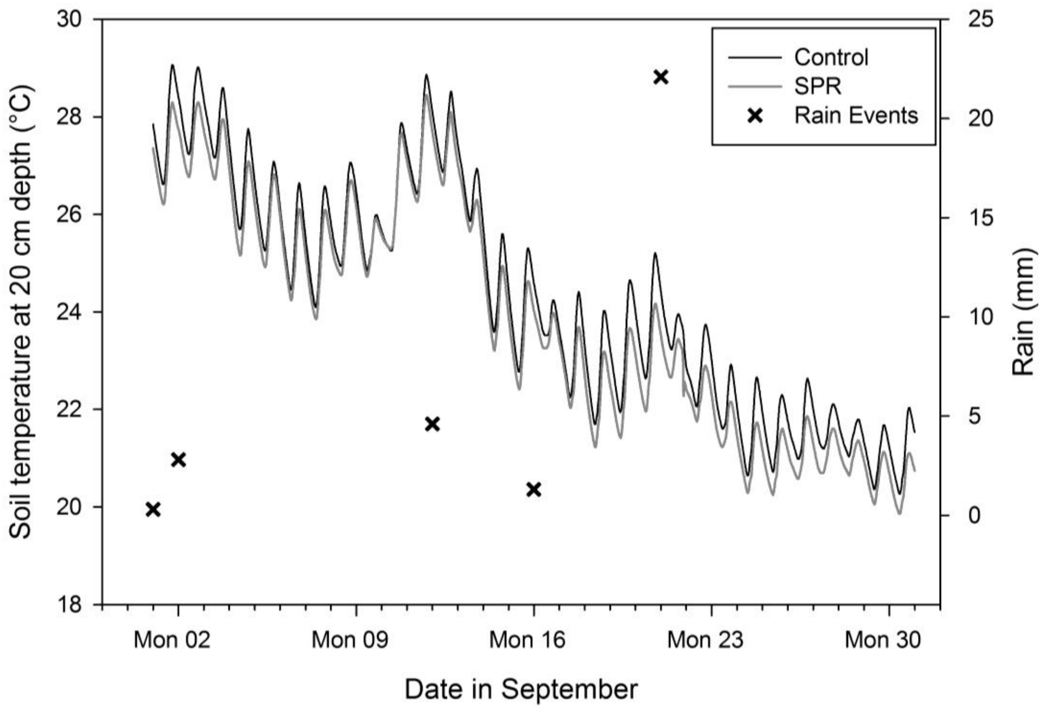

Figure 4.2. Soil temperature at 20 cm depth and rain events from September 1 to September 30, 2013 in one control and one SPR plot located less than 300 m apart, having similar aspect and distance to pavement.